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Essays on Environmental Policy Instruments, Emissions Leakage and Public Policy

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I am submitting herewith a dissertation written by Shreekar Pradhan entitled "Essays on Environmental Policy Instruments, Emissions Leakage and Public Policy." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Economics.

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Essays on Environmental Policy Instruments, Emissions Leakage and Public Policy

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dedication to my father late Laxmi Bahadur Pradhan

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Abstract

This dissertation consists of three essays related to my research on environmental policy, emissions leakage, and public policy. In the first essay, I address how open economies respond to environmental policy instruments under uncertainty. I develop a dynamic stochastic general equilibrium model for a small open economy (SOE) and evaluate the macroeconomic fluctuations in response to cap-and-trade, pollution tax, and emissions intensity standard under two shocks: productivity and terms of trade. My findings suggest that cap-and-trade policies are most effective in dampening macroeconomic volatility from productivity shock. However, under the terms of trade shock, pollution tax, and intensity target policies are as effective as the cap-and-trade policies in reducing the macroeconomic volatility of consumption and employment. The second essay addresses the effects of a general fall in service trade costs on emissions leakage. I develop a two-good (manufacturing and services) general equilibrium model of a SOE to evaluate emissions leakage from an emissions tax increase. Under free trade in manufacturing and no trade in services, no leakage occurs. Allowing for trade in services, a positive leakage is driven by income, output, and terms-of-trade effects. Calibrating the model to the Canadian macroeconomic data, I find that the emissions leakage is about 18 % lower when using trade friction levels estimated from the literature rather than assuming no trade frictions in services. In the third essay, using a data panel for American states from 1987 to 2010, I evaluate the effects of rainy day funds (RDFs) on state gross domestic product (GDP). RDFs are intended to smooth taxes and spending to alleviate fiscal stress during recessions.

While RDFs are not intended to affect the business cycle, they may do so through fund accumulation during periods of economic expansion and through fund disbursement during periods of economic contraction. Using an Arellano-Bond estimator, I find that the RDFs average output multiplier is about 1.5. The multiplier during recessionary periods is about 3.4 and during election years is as big as in recessionary periods.

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Chapter 1

Environmental Policy Instruments Under Terms of Trade and Business Cycle Uncertainties

1.1 Introduction

How do environmental policy instruments respond to trade shocks? Emerging studies show that the surge of low-cost exports from China has led to downward pressure on the price of traded goods (Kamin et al., 2006; Amiti and Freund, 2010; Mandel, 2013). China's entry into the world economy has led to a big movement in the terms of trade and an increase in imports in much of the rest of the world. We ask how such fluctuations in the terms of trade affect the choice of environmental policy instruments. The existing literature that evaluates environmental policy instruments' merits under uncertainty employs a closed-economy framework. This limits their ability to address this question.

In this study, we analyze the properties of environmental policy instruments under uncertainties for an economy open to international trade and capital flows. We document the economic responses to environmental regulation under uncertain economic growth and unanticipated import surges. To do so, we develop a small open economy (SOE) dynamic stochastic general equilibrium (DSGE) model that incorporates three environmental policy instruments which are certainty equivalent in emissions: cap-and-trade, pollution tax, and an emission intensity standard, which sets an allowed emissions level per unit of output. We introduce exogenous temporary productivity shocks to simulate uncertain economic growth and an exogenous temporary terms-of-trade shock to simulate an unanticipated import surge. We then compare the effects on key macroeconomic variables -welfare, pollution levels, outputs, consumption, investment, supply of labor and trade flows -in the economy across cap-and-trade, pollution tax, and emissions intensity standard policies.

Since Weitzman (1974) seminal article, economists have been weighing the merits of different environmental policy instruments. More recently, environmental policy's ability to respond to the business cycle has been an important metric in evaluating the policy instrument choice. Pizer (2005), Webster et al. (2010) and Ellerman and Wing (2003) compare policies indexing emissions' levels to output (known as intensity targets) to pollution taxes, and to cap-and-trade policies.[1] Fischer and Springborn (2011) and Angelopoulos et al. (2013) are among the few researchers who compared the performance of emission caps, emission taxes, and indexed standards under real business cycles. Annicchiarico and Dio (2015) compares the performance of these policy instruments under nominal shocks.

The literature mainly adopts a closed-economy framework to address these concerns. In a world with near perfect capital mobility and large international trade flows, the domestic economy is no longer fully constrained by its resources. With increased globalization the ability of environmental policy instruments to respond to international shocks is increasingly important. Our results suggest that cap-and-trade policies reduce the business cycle's intensity relative to a pollution tax or intensity target, but the cap-and-trade is most effective under a total factor productivity shock. This result is consistent with the findings of Fischer and Springborn (2011);

[1] See Peterson (2008) and Hepburn (2006) for reviews of this literature.

Annicchiarico and Dio (2015) in closed economy models. However, for a terms-of-trade shock, we all three policy instruments have a similar impact on key economic variables like consumption and employment. The cap-and-trade policy is most effective in reducing the impact of a terms-of-trade fluctuation on trade flows, but intensity targets have the lowest welfare costs.

There is a long history of literature evaluating the environmental policy's instrument choices that regulators face. Several studies have considered environmental policy instruments in the presence of uncertainty in terms of both benefit and cost when they are correlated (Quirion, 2010; Shrestha, 2001; Stavins, 1996). Antoniou et al. (2012); Heuson (2010) and Quirion (2005) have considered the effect of the choice of environmental policies on both uncertain economic growth and uncertain abatement costs. Antoniou et al. (2012) considers the instruments under international duopoly in a static model, while Heuson (2010) considers the choice under uncertainty in market power and abatement costs. Quirion (2005) considers the choice of environmental instruments under both uncertain economic growth and abatement cost under autarky. This literature has focused on either economies under autarky or has used a static modeling framework with a focus on strategic interaction among agents; thus, the literature ignores an additional channel of international trade and capital flows that may smooth business cycles' intensity.

There is considerable evidence that environmental regulation can affect international trade flows. For example, Copeland (1994) and Copeland and Taylor (2003a) recognize the interaction between international trade and pollution in a small open economy. Ederington et al. (2005) shows that environmental regulations have a significant impact on trade flows between developed and developing nations, particularly in more mobile industries. McAusland (2008) analyzes environmental regulation's impact on international trade flows while comparing pollution associated with production and consumption. This literature relies on static models and assumes a constant marginal utility of consumption. We relax those assumptions to incorporate environmental regulation's intertemporal effects under uncertainty.

The intertemporal effects are important in consumers' investment decisions under uncertainty because regulations like cap-and-trade fix the amount of emissions while inducing uncertain outcomes in the abatement cost. An emissions tax fixes the abatement cost while inducing uncertain outcomes in emissions. These effects are even more important in economies open to international trade and capital because of the additional investment channel. We contribute to this literature by showing that the choice of environmental policy instrument affects the levels of international trade and investment flows.

Most similar to our study are four recent papers examining the robustness of different environmental policy instruments to business cycle shocks. Heutel (2012) evaluates the optimal evolution of dynamic environmental regulation across the business cycle and finds that the optimal carbon taxes and cap-and-trade policies to be pro-cyclical. We employ a static exogenous environmental regulation to evaluate how economies respond to the exogenous environmental regulation rather than evaluating the path for optimal policy that policy makers may not implement during business-cycle peaks and troughs. Fischer and Springborn (2011) evaluates carbon taxes, emissions caps, and emissions intensity standards across the business cycle. The results suggest that emissions caps reduce productivity shocks' intensity relative to an emissions tax while the emissions tax is more volatile. Also, they find that an emission intensity standard has lower volatility than business as usual and is also welfare enhancing. They do not find any significant difference in welfare cost across the emissions cap and carbon tax policies. We expand on this approach by incorporating a labor-leisure choice in a small open-economy model. Most recently, Annicchiarico and Dio (2015) compares a cap-and-trade policy with an emissions tax and an intensity target in a New Keynesian model and shows that cap-and-trade policies dampen the macroeconomic dynamics but that the degree of price rigidity matters in terms of welfare. In a review article, Fischer and Heutel (2013) describes the emerging literature employing real business-cycle models to evaluate environmental policy. These models, however, do not include international trade or capital flows and, therefore, cannot consider the impact of a terms-of-trade shock. We extend these results by comparing exogenous environmental policy instruments across the business cycles for economies open to international trade and capital mobility.

The remainder of this chapter is organized as follows. Section 1.2 outlines the model and functional forms. Section 1.3 solves the model in the steady state and evaluates the policies in the absence of uncertainty. Section 1.4 presents the model's numerical analysis and evaluates environmental policy instruments in the face of increased productivity and adverse terms of trade. Section 1.5 evaluates welfare costs across the environmental policy instruments under the uncertainties. Section 1.6 concludes this chapter.

1.2 The Model

We consider an economy that has a continuum of households with identical preferences. The infinitely lived households consume domestically produced and imported goods and enjoy leisure activities to maximize expected life-time utility. Households supply labor and capital to firms, which produce goods using two factor inputs: labor and capital. Pollution is generated during the production of goods, and in our model pollution is treated as an input. Pollution is assumed to be generated in proportion to fossil-fuel use in the production process. Alternatively, a fixed amount of pollution per unit of fossil fuel is implicit in our model.

The economy under consideration is open to free trade and capital is allowed to flow internationally; however, labor is immobile. The domestic government's role is limited to implementing an environmental policy and redistributing revenues, if any, to households in a lump-sum. Therefore, in this economy, outputs are either domestically consumed, invested, or exported. If domestic absorption exceeds production, the economy imports from the rest of the world, meaning that households can satisfy both their consumption and investment needs by raising foreign debt. This point is the key point of departure from models in the literature.[2] Further, we assume that our economy is small compared to the rest of the world's, meaning the domestic environmental policy change will not affect capital's international interest rate and is exogenous to this economy. The firms are price takers, and they make export and import decisions given the world's fixed prices.

We solve the problems of households and firms by assuming a representative household and firm.

Households' problem

With capital mobility, households can borrow internationally but face an upward-sloping supply schedule of borrowing because of a country-specific risk premium that increases with the level of debt. We endogenize the interest rate using the risk premium, another key distinction from the literature. In closed economy models, the rate of return from domestic investments determines the real interest rate (See Fischer and Springborn (2011) and Angelopoulos et al. (2013)). For a small open economy, the international capital market exogenously determines such an interest rate.[3] To resolve this problem, we use a debt-elastic interest-rate premium widely employed in the international economics literature (see Schmitt-Grohé and Uribe (2003); Mendoza and Uribe (2000); Schmitt-Grohé and Uribe (2001)). Under the debt-elastic interest rate, the domestic interest rate is a function of an exogenous international interest rate and a premium

$$R_t = R^* + P(exp^{\widetilde{D_t} - \overline{D}} - 1) \tag{1.1}$$

[2] See Fischer and Springborn (2011); Angelopoulos et al. (2013) and Annicchiarico and Dio (2015). Note that these studies assume a closed economy and require that domestic absorption be equal to domestic production each period.

[3] This implicitly makes the model's steady state dependent on initial conditions. In other words, the temporary shocks have long-run effects on an open economy's state, creating a random walk component in such models' dynamic equilibrium.

where R^* is the exogenous interest rate in international capital markets, $P(.)$ is the economy's risk premium, $\widetilde{D_t}$ is the economy's aggregate debt, and $\overline{D}$ is the steady-state debt level. Borrowing costs increase with the stock of debt issued ($P' > 0$). In a representative economy, $\widetilde{D_t} = D_t$, a representative household's debt level.

The representative household maximizes her expected lifetime utility in present value

$$\max_{C_t, H_t} \; E_0 \sum_{t=0}^{\infty} \beta^t \, U(C_t, H_t) \tag{1.2}$$

where $\beta \in (0,1)$ is the fixed subjective discount factor, C_t is consumption, and H_t represents the amount of labor the household supplies. We assume that the representative household is endowed with one unit of time, and we abstract from population growth. Thus, $1 - H_t$ represents leisure activities. The utility's functional form satisfies: $U_C > 0$, $U_H < 0$, $U_{CC} < 0$, $U_{HH} < 0$ and $U_{CH} > 0$.

The household is subject to the following budget constraints:

$$D_t = (1 + R_{t-1})D_{t-1} + p_t C_t + I_t + \Phi(K_t - K_{t-1}) - w_t H_t - r_t K_{t-1} - G_t - \Pi_t \tag{1.3}$$

where D_t is the household's stock of foreign debt, p_t is the relative price of consumption, K_t is the stock of capital, I_t is investment, $\Phi(.)$ is investment-related adjustment cost (with $\Phi(0) = 0$, $\Phi'(0) = 0$), w_t is the wage-per-unit of labor supplied to firms, r_t is the rental rate per unit of capital supplied to firm, G_t is a lump-sum transfer from government(if any), and Π_t represents a dividend from firms. We consider the debt to be denominated in terms of the world's export price of outputs. In our model, all prices are relative to the world's price of outputs.

Capital stock evolves as

$$K_t = I_t + (1 - \delta)K_{t-1} \tag{1.4}$$

where δ is the depreciation rate.

The representative household chooses processes $[C_t, H_t, K_t, D_t]_{t=0}^{\infty}$ to maximize her life-time expected utility Eq.(2.1) subject to the budget constraint Eq.(1.3), a no-ponzi constraint, $\lim_{j\to\infty} E_t \left(\frac{D_{t+j}}{\prod_{s=1}^{j}(1+R_s)} \right) \leq 0$ and initial stocks of capital and a debt. With λ_{1_t} being the Lagrangian multiplier for the budget constraint, the representative household's maximization problem can be represented by the following Lagrangian:

$$\max_{C_t,H_t,K_t,D_t} \mathscr{L} = E_t \sum_{t=0}^{\infty} \beta^t \Bigg[U(C_t, H_t) + \lambda_{1_t} \Big\{ D_t - (1+R_{t-1})D_{t-1} - p_t C_t - K_t + (1-\delta)K_{t-1} - \Phi(K_t - K_{t-1}) + w_t H_t + r_t K_{t-1} + G_t + \Pi_t \Big\} \Bigg] \tag{1.5}$$

The first order conditions are:

$$C_t : U_{C_t}(C_t, H_t) = \lambda_{1_t} p_t \tag{1.6}$$

$$H_t : -U_{H_t}(C_t, H_t) = \lambda_{1_t} w_t \tag{1.7}$$

$$K_t : \lambda_{1_t} \Bigg[1 + \Phi'(K_t - K_{t-1}) \Bigg] = \beta\, E_t \Bigg[\lambda_{1_{t+1}} \Big\{ (1 - \delta + r_{t+1} + \Phi'(K_{t+1} - K_t) \Big\} \Bigg] \tag{1.8}$$

$$D_t : \lambda_{1_t} = \beta\, E_t\, \lambda_{1_{t+1}}\, (1 + R_t) \tag{1.9}$$

These are standard Euler equations. Eq. (1.6) shows that households' optimal consumption level occurs when marginal utility from consumption is equal to the marginal utility from wealth. In Eq. (1.7), we see that households optimally supply labor when marginal utility from leisure is equal to the wage per unit of labor supplied. Eq. (1.8) shows that households optimally invest one unit of capital when marginal cost of the investment (in terms of utils) is equal to the expected present value of marginal benefit of the investment next period. The investment's marginal cost is shown in the LHS of Eq. (1.8), and the expected present value of marginal benefit of the investment next period is shown in the equation's RHS. Likewise, Eq. (1.9) shows the cost and benefit of borrowing a unit of debt. The LHS of Eq. (1.9) is the utility the agent receives from one unit of borrowing while the RHS is the expected present value of the debt's repayment cost(in utils).

Firms' problem

We model the representative firm's problem as follows; The representative firm maximizes profit

$$\max_{K_t, M_t, H_t} E_t \sum_{t=0}^{\infty} \beta^t \Pi_t = E_t \sum_{t=0}^{\infty} \beta^t \Big[Y_t(A_t, K_{t-1}, M_t, H_t) - w_t H_t - r_t K_{t-1} - q_t M_t \Big] \quad (1.10)$$

where $Y_t = A_t K_{t-1}^{\alpha_1} M_t^{\alpha_2} H_t^{1-\alpha_1-\alpha_2}$, A_t is the total factor productivity (exogenous), M_t is the fossil fuel level (or pollution level proportional to the fossil fuel level), and q_t is the price of fossil fuel.[4] Note that q_t also represents per-unit emission tax since M_t represents pollution level. The capital share in output is α_1, and the fossil-fuel expenditure's share in output is α_2; thus, $1-\alpha_1-\alpha_2$ is the share of labor in production. The factor shares, α_1 and α_2, are bounded by $(0, 1)$. We assume that the economy has an abundant supply of fossil fuels and that the fossil fuel expenditure $q_t M_t$ remains within the economy as $q_t M_t$ is treated as the emissions tax revenue transferred to the households in a lump sum.[5] Note that output is the numeraire good; thus, the prices are relative to the output's export price.

In the absence of environmental regulation (i.e., under business as usual), Eq. (1.10) represents the firms' problem. Following Fischer and Springborn (2011), we abstract pollution from the households' welfare function since we intend to capture only the environmental regulation's welfare cost. This welfare cost is measured through the reduced consumption of households keeping fixed labor, which is a standard procedure in the DSGE framework. To address the externalities associated

[4] Fischer and Springborn (2011) also used a similar Cobb-Douglas form of production.

[5] In the model, firms perfectly comply with environmental regulations. Since fossil fuel expenditure is observable and is accurately measured, the treatment of fossil fuel expenditure is justifiable.

with pollution emissions, we assume the government imposes an environmental policy $CAP(Y_t)$, which could be a cap-and-trade, an emissions tax, or an emission intensity target. These policies are cost-less to administer, and firms comply with the environmental policies. Cap-and-trade firms are required to possess a permit to emit a unit of pollution in each period and pay a permit price (the constraint's shadow value in the case of cap-and-trade). In this case, $CAP_t = M_t$, which is exogenously fixed. Under an emissions-tax policy, firms are required to pay a tax for each unit of emissions generated. In the case of an emission intensity target, the policy exogenously fixes a ratio of M_t to Y_t. Note that these policies are exogenously chosen to reduce emissions and could be sub-optimal.[6]

We assume that the environmental policy is binding on firms

$$CAP(Y_t) = M_t \tag{1.11}$$

and the Lagrangian of the representative firm's problem is

$$\begin{aligned}\max_{H_t, K_t, M_t} \mathscr{L} = E_t \sum_{t=0}^{\infty} \beta^t \Big[& Y_t(A_t, K_{t-1}, M_t, H_t) - w_t H_t - r_t K_{t-1} - q_t M_t \\ & + \lambda_{2_t} \Big(CAP(Y_t) - M_t \Big) \Big]\end{aligned} \tag{1.12}$$

where λ_{2_t} is the policy constraint's shadow price.

The first order conditions are

$$H_t : Y_{H_t}(A_t, K_{t-1}, M_t, H_t)(1 + \lambda_{2_t} Cap_{Y_t}) = w_t \tag{1.13}$$

$$K_t : Y_{K_t}(A_{t+1}, K_t, M_{t+1}, H_{t+1})(1 + \lambda_{2_{t+1}} Cap_{Y_{t+1}}) = r_{t+1} \tag{1.14}$$

$$M_t : Y_{M_t}(A_t, K_{t-1}, M_t, H_t)(1 + \lambda_{2_t} Cap_{Y_t}) = q_t + \lambda_{2_t} \tag{1.15}$$

[6] Heutel (2012) assumes efficient environmental policy and analyzes how that optimal policy should evolve across the business cycle. We focus on static policies, which are certainty equivalent in emission reductions, and compare the responses of static policies across the real business cycle and terms-of-trade shocks.

These are standard Euler equations for the firm's problem. Firms choose factor inputs: labor (Eq. (1.13)), capital (Eq. (1.14)), and fossil fuels (Eq.(2.9)) based on their marginal factor returns.

Our economy responds to two exogenous shocks: home productivity and terms of trade. The economy may face a sudden improvement in technology, leading to a boom in the economy. We model such economic growth through a temporary positive shock to the total factor productivity. On the other hand, the economy may face a deterioration in terms of trade because of import competition from sudden surge-of-trade flows from countries like China. We model such terms of trade shock through an exogenous positive temporary shock to consumption's relative price. These two shocks follow stationary autoregressive processes as below:

$$\log A_t = \rho_A \log A_{t-1} + \epsilon_{A_t} \tag{1.16}$$

$$\log p_t = \rho_p \log p_{t-1} + \epsilon_{p_t} \tag{1.17}$$

where, ρ_A and ρ_p are persistency of the shocks and are bounded by 0 and 1. The parameters ϵ_{A_t} and ϵ_{p_t} are serially uncorrelated shocks normally distributed with mean zero and standard deviations σ_A and σ_p, respectively.

The following market-clearing conditions are satisfied. The representative firm's zero profit condition is

$$Y_t(A_t, K_{t-1}, M_t, H_t) = w_t H_t + r_t K_{t-1} + q_t M_t \tag{1.18}$$

and the resource constraint in an open economy is

$$D_t = (1 + R_{t-1}) D_{t-1} - Y_t + p_t C_t + I_t + \Phi(K_t - K_{t-1}) \tag{1.19}$$

Note that, $q_t M_t$ is eliminated from the resource constraint because of our assumption that the economy has an abundant supply of fossil fuels and that firms' expenditure on fossil fuels in the form of pollution tariff revenue is returned to the households in a lump sum.

The trade balance is defined as domestic production minus domestic absorption.

$$tb_t = Y(A_t, K_{t-1}, M_t, H_t) - p_t C_t - I_t - \Phi(K_t - K_{t-1}) \tag{1.20}$$

The economy's net asset position captures the capital flow, and the current account is the net of the trade balance and the serviced debt amount.

$$ca_t = tb_t - R_{t-1} * D_{t-1} \tag{1.21}$$

Note that the government balances the budget each period, and G_t is the transfer from the government. Then, the import tariff revenue or any government collection from environmental policy are eliminated from the resource constraint since these components are returned to the representative household in a lump sum.

1.2.1 Functional Forms

We employ a Cobb-Douglas utility function with an intertemporal elasticity of substitution across periods as is standard in the literature

$$U(C_t, H_t) = \frac{[C_t^{\alpha}(1 - H_t)^{1-\alpha}]^{1-\sigma} - 1}{1 - \sigma} \tag{1.22}$$

where, α is the share of income that households spend on consumption, and σ is the intertemporal elasticity of substitution across periods (also known as the relative risk-aversion parameter).

Production has a Cobb-Douglas function with the constant returns to scale $Y_t = A_t\ K_{t-1}^{\alpha_1}\ M_t^{\alpha_2}\ H_t^{1-\alpha_1-\alpha_2}$. The adjustment cost of investment has a quadratic function $\Phi(K_t - K_{t-1}) = \frac{\phi}{2}(K_t - K_{t-1})^2$ where, $\phi(> 0)$ is an adjustment cost shift parameter.

1.3 Steady State Analysis

This section solves for the economy's response to the introduction of each of the selected policies in the absence of shocks. In the steady state, there is no uncertainty in the economy, and the system is in long-run equilibrium; therefore, we abstract by using time subscripts. Incorporating the functional forms and the household's and firm's problems, the steady state is represented by the following ratios

$$z : \frac{H}{1-H} = \frac{\alpha}{1-\alpha}(1-\alpha_1-\alpha_2)\,\frac{(1+\lambda_2 CAP_Y)}{p\,c} \tag{1.23}$$

$$k : \frac{K}{Y} = \frac{\alpha_1\,(1+\lambda_2 CAP_Y)}{R^*+\delta} \tag{1.24}$$

$$m : \frac{M}{Y} = \frac{\alpha_2(1+\lambda_2 CAP_Y)}{q+\lambda_2} \tag{1.25}$$

$$c : \frac{C}{Y} = \frac{1}{p}\left(1-\delta k - R^*\bar{d}\right) \tag{1.26}$$

where, z is the labor-leisure ratio, and k, m and c are the capital-to-output, emission-to-output, and consumption-to-output ratios, respectively. $\bar{d}$ is the long-run debt such that the debt-to-output ratio is equal to the long-run ratio of the small economy under consideration.

No policy

In the environmental policy's absence, $\lambda_2 = 0$ yielding the capital-to-output ratio $k = \frac{\alpha_1}{R^*+\delta}$, emission-to-output ratio $m = \frac{\alpha_2}{q}$, and the consumption-to-output ratio $c = \left(1-\frac{\delta\alpha_1}{R^*+\delta}-R^*\bar{d}\right)\frac{1}{p}$. We note that the ratio c is smaller compared to that in a closed economy because of the debt-servicing requirement in an open economy. We find the labor-leisure ratio $z = \frac{\alpha}{1-\alpha}\frac{(1-\alpha_1-\alpha_2)}{\left(1-\frac{\delta\alpha_1}{R^*+\delta}-R^*\bar{d}\right)}$ under no policy. Increases in the debt-to-output ratio are associated with increased employment in this economy compared to the closed economy since more output is needed to service the debt.

Cap and Trade

Under a cap-and-trade system, the government imposes a fixed cap on emissions to regulate pollution. In this policy, the emission is bounded by exogenous level of $\bar{M} = CAP$ and $CAP_Y = 0$. This provides emission-to-output ratio $m = \frac{\alpha_2}{q+\lambda_2}$, capital-output ratio $k = \frac{\alpha_1}{R^*+\delta}$, and consumption-to-output ratio of $c = \left(1 - \frac{\delta\alpha_1}{R^*+\delta} - R^*\bar{d}\right)\left(\frac{1}{p}\right)$. We find the labor-leisure ratio $z = \frac{\alpha}{1-\alpha}\frac{(1-\alpha_1-\alpha_2)}{\left(1-\frac{\delta\alpha_1}{R^*+\delta}-R^*\bar{d}\right)}$. Under this policy, the effective shadow price $\lambda_2 = \frac{\alpha_2 - q\,m}{m}$ restricts the emissions level to $\bar{M}$.

Tax

In the case of an environmental tax policy, the government imposes a constant pollution tax (T) charged for each unit of pollution. In our model, the effective shadow price λ_2 is the corresponding emissions tax rate that reduces emissions to CAP (i.e. $\lambda_2 = T$). The tax rate restricts the emissions level in the steady state equivalent to that under the cap-and-trade policy. In such a case, tax revenue is distributed to households in a lump sum transfer and $CAP_y = 0$. We find the emission-to-output ratio $m = \frac{\alpha_2}{q+T}$, capital-to-output ratio $k = \frac{\alpha_1}{R^*+\delta}$, and consumption-to-output ratio of $c = \left(1 - \frac{\delta\alpha_1}{R^*+\delta} - R^*\bar{d}\right)\left(\frac{1}{p}\right)$. We find the labor-leisure ratio $z = \frac{\alpha}{1-\alpha}\frac{(1-\alpha_1-\alpha_2)}{\left(1-\frac{\delta\alpha_1}{R^*+\delta}-R^*\bar{d}\right)}$. These ratios are similar to that under the cap-and-trade policy. The tax rate required to restrict the emission under this policy is $T = \frac{\alpha_2 - q\,m}{m}$.

Intensity Target

For an intensity target, the government requires a maximum fixed ratio of emissions-per-unit output $\bar{m} = \frac{M}{Y}$. Then, the intensity target policy can be represented by $CAP(Y) = \bar{M} = \bar{m}\ Y$ where $\bar{M}$ is the emission level restricted under the cap-and-trade policy. Since $CAP_Y = \bar{m}$ and emission-to-output ratio $m = \bar{m}$, we find the capital-to-output ratio $k = \frac{\alpha_1(1+\lambda_2\bar{m})}{R^*+\delta}$. The consumption-to-output ratio $c = \frac{1}{p}\left(1 - \frac{\delta\alpha_1(1+\lambda_2\bar{m})}{R^*+\delta} - R^*\bar{d}\right)$. The labor-leisure ratio $z = \frac{\alpha}{1-\alpha}\frac{(1-\alpha_1-\alpha_2)(1+\lambda_2\bar{m})}{\left(1-\frac{\delta\alpha_1(1+\lambda_2\bar{m})}{R^*+\delta}-R^*\bar{d}\right)}$. Under this policy, the effective shadow price $\lambda_2 = \frac{\alpha_2 - q\bar{m}}{\bar{m}(1-\alpha_2)}$ restricts emissions to the same level under the cap-and-trade policy. The shadow price is bigger than that under the cap-and-trade policy, meaning the emission-to-output ratio under the intensity target that restricts the emissions level equivalent to the cap-and-trade policy is smaller, yielding outputs under this policy higher than those under the cap-and-trade policy.

1.4 Numerical Analysis

1.4.1 Data Aggregation and Model Calibration

In this section, we summarize the long-run empirical relationships used to identify our model's deep structural parameters. The long-run relationship corresponds to Canada's historical annual expenditure-based GDP for 1981-2010. This information is available from Statistics Canada.[7] The model is further parameterized such that the calibrated economy's structure simulates the Canadian economy's business cycles.[8] To be consistent with our model specification, GDP is calculated by netting out government expenditure. Households' consumption includes goods and services, investment includes gross fixed-capital formation, and net export of goods and services accounts for trade flows. For the terms of trade, we use the export and import prices in the Penn World Table, which is available for 1950-2010.[9].

The deep structural parameter values used in the steady state to represent Canada's historical economy are shown in Table 2.1, and the key macroeconomic ratios in the steady state are shown in Table 1.2. During the period considered, households' consumption of goods and services accounts for 68% of GDP, investment accounts for 26%, and the net export of goods and services accounts for the remaining GDP (6%). The average compensation to employees is 45% of gross outputs during

[7]Source: Statistics Canada. Table 380-0106 - Gross domestic product.
[8]The second moments in our model are consistent with the literature.
[9]For more details, see PWT 8.1 in Feenstra et al. (2015)

the period.[10] We set 0.45 as the labor share in outputs. For the share of fossil fuel expenditures, we follow Fischer and Springborn (2011) and estimate the share as 9% of GDP.[11] We set the share of capital $\alpha_1 = 0.46$ and the share of fossil fuel expenditure $\alpha_2 = 0.09$. The exogenous international interest rate is fixed at 4% per annum; the annual depreciation rate of capital is fixed at 10%; the intertemporal elasticity of substitution across periods is fixed at 2. These amounts are standard in the literature. The persistency parameters and the standard deviation correspond to data from the Penn World Table.[12] We estimate uni-variate AR(1) processes for the total factor productivity and the relative price of imports-to-exports to set the persistency of total factor productivity and the terms of trade, which are 0.533 and 0.319, respectively. The corresponding standard deviations of the shocks are 0.0149 and 0.0296, respectively. Since our sample period captures recent years, the estimates for the total factor productivity shock are a slightly higher than those in the literature (Uribe, 2013).

The parameters' values $\bar{d}$, α, ψ and ϕ are chosen to mimic the dynamic performance of the Canadian economy's business cycles as found in the literature. We set $\bar{d} = 0.909$ such that the long-run trade balance to GDP ratio in our model is 0.0638 to match the historical average trade flow share of goods and services to the GDP in the sample period. The share of income that households spend on consumption is calibrated as 33% ($\alpha = 0.33$) such that households' labor supply in the steady state is 27%. The country-specific risk premium is set at $\psi = 0.0742$ to match the dynamic performance of trade balance and current account as shown in the literature. We choose a hp-filter of smoothing parameter 100 to filter the trend in our calibrated model. Table 1.3 provides the calibrated model's theoretical second moments.

[10] The compensation is calculated over the sample period. Source: Statistics Canada. Table 383-0032 - Multifactor productivity, gross output, value-added, capital, labor and intermediate inputs at a detailed industry level by the North American Industry Classification System (NAICS).

[11] We also find that the share of abatement cost expenditure in manufacturing outputs is 7.5% in Canada as reported in surveys conducted during 1996-2010. However, these estimates are not reported regularly (Source: Canadian Statistics).

[12] See appendix for the details.

The relative prices of consumption and fossil fuels in terms of the output's world price are set at 1 in the steady state. The total factor productivity is also set at 1 in the steady state. These normalizations let us evaluate the model's responses to shocks as cyclical responses rather than as a trend.

Table 1.1: Parameters in the Model

Parameter	Description	Value
	Deep structural parameters	
R^*	Exogenous international interest rate	0.04
α_1	Capital share in output	0.46
α_2	Energy expenditure share in output	0.09
$1-\alpha_1-\alpha_2$	Labor share in output	0.45
$\bar{h}$	Household's endowment of labor	1
δ	Annual depreciation rate	0.1
ρ_A	Autocorrelation of total factor productivity shock	0.533
ρ_p	Autocorrelation of terms-of-trade shock	0.319
σ_A	Standard deviation of the productivity shock	0.0149
σ_p	Standard deviation of the terms-of-trade shock	0.0296
$\frac{\bar{tb}}{\bar{Y}}$	Trade balance-to-output ratio	0.0644
	Calibrated parameters	
σ	Intertemporal elasticity of substitution (risk parameter)	2
ϕ	Shift parameter in capital adjustment cost	0.008
ψ	Country specific risk-premium	0.0742
α	Share of consumption expenditure on households' income	0.33
$\bar{d}$	Long-term debt level	0.909

1.4.2 Deterministic Responses to Environmental Policies

The economic responses under a deterministic case is shown in Table 1.4. In the absence of uncertainty, no difference exists between the cap-and-trade and tax policies; but the intensity target produces higher levels of consumption, labor supply, outputs, investment, and capital stocks than the cap-and-trade or tax policies. These findings

Table 1.2: Empirical and Steady State Performance of the Model

Description	Canadian Data (1981-2010)	Model
Trade balance-to-GDP ratio	6.44%	6.38%
Consumption-to-GDP ratio	67.68%	64.70%
Debt-to-GDP ratio	160.90%	159.49%

Table 1.3: Theoretical Second Moments of the Model

	Standard deviation	Auto-correlation	Correlation with GDP
GDP	2.20	0.47	1
Consumption	0.71	0.54	0.91
Capital	1.01	0.43	0.97
Labor supply	1.15	0.49	0.98
Trade-balance/GDP		-0.20	-0.18
Current account/GDP		-0.18	-0.19

Note: The theoretical second moments are for one standard deviation shock to total factor productivity. Standard deviations are measured in percentage points from the theoretical mean.

Table 1.4: Steady-State Levels Across Policies

	Policy Cases				% Change from No Policy		
Variables	No policy	Cap-and-Trade	Tax	Intensity Target	Cap-and-Trade	Tax	Intensity Target
Output	0.570	0.550	0.550	0.568	-3.4%	-3.4%	-0.2%
Consumption	0.346	0.333	0.333	0.341	-3.8%	-3.8%	-1.3%
Investment	0.188	0.181	0.181	0.191	-3.4%	-3.4%	1.7%
Labor supply	0.272	0.272	0.272	0.278	0.0%	0.0%	2.2%
Capital Stock	1.876	1.811	1.811	1.908	-3.4%	-3.4%	1.7%
Emissions	0.051	0.041	0.041	0.041	-20%	-20%	-20%

are consistent with our analytical analysis. GDP decreases by 3.4% under the cap-and-trade and tax cases while it decreases by 0.2% under the intensity target. Consumption falls by 3.8% from no policy under the cap-and-trade or tax cases, but the fall is 1.3% under the intensity target. Investment decreases by 3.4% under the cap-and-trade and tax cases while investment increases by 1.7% under the intensity target case. Under the cap-and-trade and tax cases, the labor supply remains similar to the no-policy case, but the supply of labor increases by 2.2% under the intensity target. This means, to maintain the same emissions level from the cap-and-trade case under the intensity target, firms substitute emissions with labor and capital which are clean inputs. Furthermore, the required ratio under the intensity target to maintain the same level of emissions, as explained in the analytical analysis, is stricter than under the cap-and-trade. As a result, the labor supply and investment are higher than the no-policy baseline, but the increment in inputs is not that much higher than in the no-policy case to affect the outputs in order to increase. Also, the permit price under the intensity target case must increase by 27.4% compared to the cap-and-trade case.

1.4.3 Uncertainty and Environmental Policy

This section evaluates the dynamic properties of the emissions tax, cap-and-trade, and intensity target in the presence of uncertainties. We simulate the uncertain economic growth by employing an exogenous temporary stochastic shock to the total factor productivity and separately, a shock to the terms of trade through an exogenous temporary positive stochastic shock to the world's relative price of imports to exports, meaning an adverse terms-of-trade shock.[13] We compute the first and second moments of the key macroeconomic variables and trace their impulse response functions. The simulation results are computed using the "pure" perturbation method, which relies on a second-order Taylor approximation of the model around its initial steady state.[14] Table 1.5 shows the environmental policies imposed in our model.

[13] Our relative price of consumption is the ratio of import price to export price, which is inverse to the terms of trade definition.

[14] The model is solved in Dynare. See Adjemian et al. (2011) for more details.

Table 1.5: Static Level of Environment Policies Imposed in the Model

	Cap-and-Trade	Emissions Tax	Intensity Target
Policy	0.041	0.207	0.722

Note: The Cap-and-Trade policy 0.041 represents 20% reduction of emissions from the no policy case. Emissions Tax of 0.207 represents per unit emissions tax and intensity target of 0.722 is the fixed ratio of emission to output. Note that policies in the steady state yield the 20% reduction of emissions from the no policy case. Also, note that a stricter intensity target is necessary to maintain the same level of emissions.

Productivity Shock

In this section, we describe the economy's responses under uncertain economic growth as the result of one period of temporary productivity shock with a magnitude of one standard deviation. First, we solve the model for the no-policy case, a baseline scenario with no additional environmental regulations. Then as in Fischer and Springborn (2011), we model a 20% emission reduction from the steady-state level of emissions from the no-policy case.[15] Therefore, we model an emissions cap at 20% below the baseline emissions level and then introduce emission taxes and intensity targets such that the amount of emission reductions is the same across each of the environmental policies in the steady state.

Figure 1.1 and 1.2 plot the impulse response functions of several variables on interest to a total factor productivity shock of 1 standard deviation in period 0 under the four different policies: i) no policy, ii) cap-and-trade, iii) emission tax, and iv) intensity target. The model is simulated for 10,000 periods, and the first 100 periods are discarded. We use the Hodrick-Prescott filter (with a smoothing parameter of 100) before recording the statistical moments, and the responses are plotted in terms of deviation from the steady-state level of each variable. The model predicts an

[15] The European Union has a target reducing emissions 20% from 1990 levels by 2020, and both the Waxman-Markey and Kerry-Lieberman bills proposed in the U.S. Congress targeted a 20% emissions reduction.

increase in outputs, consumption, labor, investment, debt and interest rate as well as a deterioration of the trade-balance. The consumption's initial response is relatively smaller by an order of magnitude of two than the initial investment response. As the domestic absorption (consumption and investment) is higher than the domestic production, the trade balance's initial response is negative, leading to a rise in debt and, thus, the risk premium on interest rate. As a result, the effective interest rate increases, affecting households' consumption smoothing behavior over time. This effect means that although consumption is dominated by the positive income effect compared to the negative price effect, households save most of their increased income, showing the price effect's significant influence on consumption.

Under the cap-and-trade policy, which fixes emissions level, outputs are dampened. As a result, households save relatively less to smooth consumption compared to the no-policy case. The effective interest rate increases relatively less than in the no-policy case, leading to dampened consumption over time. However, under the emissions tax policy, which fixes the emissions' price allow emissions to rise leading to relatively higher outputs than the cap-and-trade policy. As a result, households save relatively more under the emissions tax policy to smooth consumption but not as much as in the no-policy case. The effective interest rate's increase under the emissions tax is relatively higher than under the cap-and-trade policy but not higher than in the no-policy case. This leads to dampened consumption but relatively less dampened than with the cap-and-trade policy. Under the intensity target, a stricter level of emissions-to-output ratio is required to maintain the same emissions level under the cap-and-trade, leading to a relatively bigger rise in outputs and thus savings, which dampen consumption over time but less than in the no-policy case.

The literature discusses variations in economic variables across the business cycle to evaluate environmental policies. We follow this precedent by calculating the coefficient of variation (CV) across the business cycle for each environmental policy and for the no-policy baseline. The results are reported in Table 1.6. Each CV provides a measure of the corresponding variable's dispersion as a percentage of its theoretical mean. We find that the cap-and-trade policy consistently has the lowest CV for the economic variables. For emissions, this finding is obvious; after the positive productivity shock, the emissions level remains unchanged at 20% below the baseline case, so there is no variation. This inflexible emissions cap reduces the positive productivity shock's benefits so that output, consumption, investment, labor, capital, debt, and trade flows all increase less under a cap-and-trade policy than under the other policy instruments. Thus, the cap-and-trade policy reduces the real business cycle's severity, a finding which is consistent with the results in Fischer and Springborn (2011).[16] Under the tax policy, the variations of consumption, labor, and output are similar from those of the no policy, except that investment is higher in the tax case. Under the intensity target, variations are not very different than in the no-policy case.

We also check the results' robustness by employing the higher magnitude and higher persistency shock, which helps to magnify the differences in responses across the policies. The results for the shock of 1.5 standard deviation with a 90% persistency level are shown in the appendix (Table A.2 and in Figures A.1 and A.2). We find similar results. The cap-and-trade policy dampens the shock's intensity, and the emissions tax policy has higher variation, whereas the intensity target policy has variation similar to that of the no-policy case.

Terms of Trade Shock

In this section, we describe the economy's dynamic responses to the negative terms of trade shock as a result of import competition, such as a surge of trade flows from China. To do so, we model the terms-of-trade shock as a one standard deviation positive shock to the relative price of consumption. As under the productivity shock, the model is solved for the no-policy case and for the three environmental policies that

[16]The model is symmetric so a negative productivity shock modeling the business cycle's trough would give the same results. Reduced economic activity would reduce both the cap's shadow price and the shock's negative impact, once again dampening the business cycle.

Table 1.6: Variations Under the Productivity Shock

Variables	No policy	Cap	Tax	Intensity Target
Consumption	0.71	0.61	0.71	0.71
Labor	1.15	1.01	1.15	1.14
Investment	10.29	8.86	10.48	10.13
Output	2.20	1.92	2.21	2.19
Emission	2.20	0.00	2.21	2.19

Note: The table shows the coefficient of variations for 1 standard deviation positive temporary shock to the total factor productivity. The coefficient of variation is the standard deviation divided by the theoretical mean level (in percentage points).

reduce 20% emission from the no-policy case's emissions level in the steady state. As before, the model is simulated for 10,000 periods, the first 100 periods are discarded, and the Hodrick-Prescott filter (with a smoothing parameter of 100) is employed.

Figure 1.3 and 1.4 plot interesting variables' impulse response functions across the four policies: i) no policy, ii) cap-and-trade, iii) emission tax, and iv) intensity target. The negative terms-of-trade shock generate the inverse of the variables' path from the productivity shock. As evident in the empirical literature, the model predicts a decline in consumption, outputs, labor, and investment. Also, in response to the shock, the trade balance deteriorates and debts increase, leading to an increased interest rate, also noted under the productivity shock. In response to the negative terms-of-trade shock, the initial decline in consumption is relatively larger than the decline in investments. Households dissave in response to declining outputs to smooth consumption even though consumption is declining. In the model, however, the initial decline in domestic absorption (consumption and investment) is smaller than the decline in domestic production, leading to deterioration in the trade balance. This

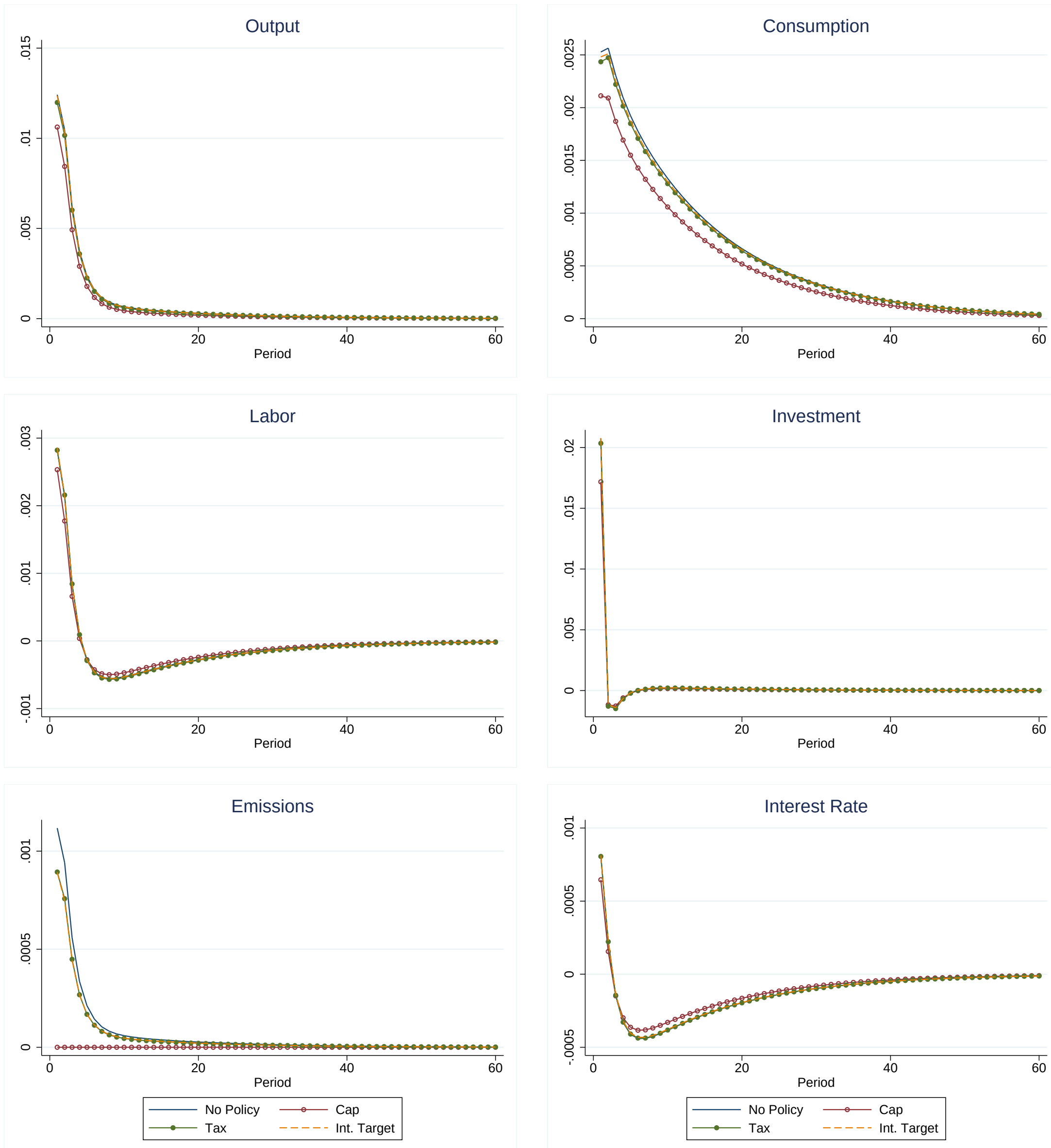

Figure 1.1: Impulse Responses Under the Productivity Shock (Panel A)

Note: The figures show the impulse response functions of output, consumption, labor, capital, emissions, debt, current account, and trade balance in response to the positive productivity shock of one standard deviation as shown on the bottom-right corner panel of Figure 1.2. Zero on the vertical axis on each graph represents corresponding variable's steady-state level. The responses are in terms of deviation from the steady-state level.

deterioration leads to an increase in the effective interest rate, suggesting an increase in return on investment. Thus, both the income effect and the price effect negatively

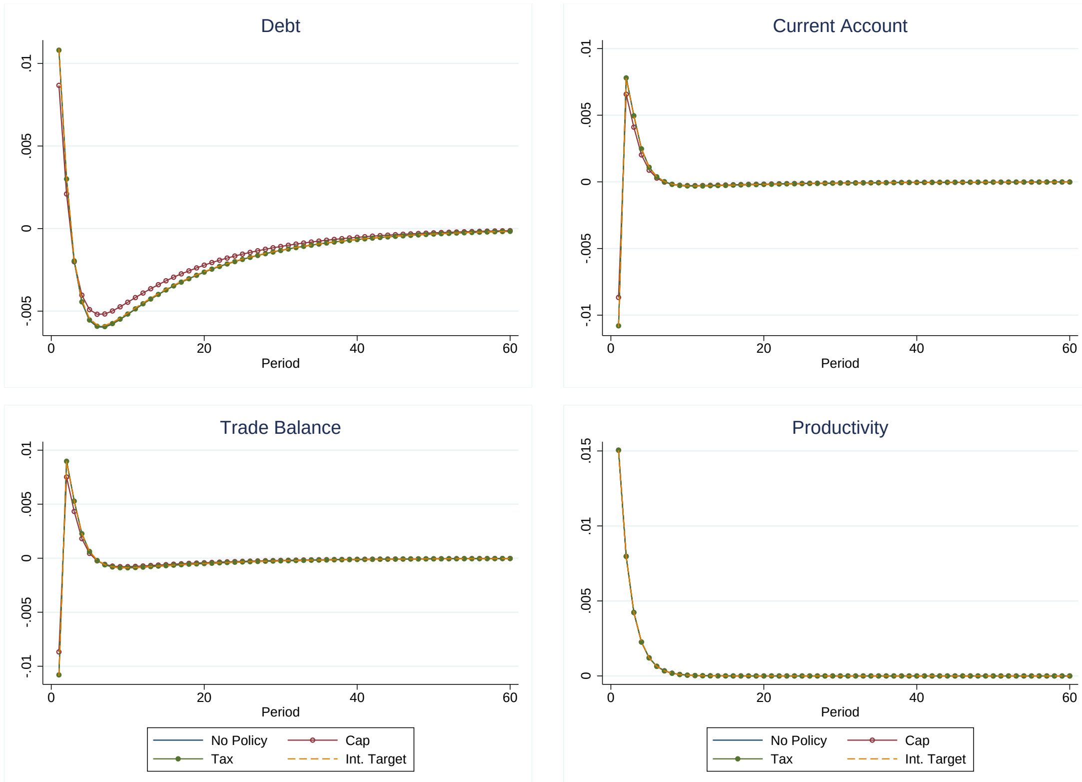

Figure 1.2: Impulse Responses Under the Productivity Shock (Panel B)

Note: Note: The figures show the impulse response functions of output, consumption, labor, capital, emissions, debt, current account and trade balance in response to the positive productivity shock of one standard deviation as shown on the bottom right corner panel. Zero on the vertical axis on each graph represents corresponding variable's the steady state level. The responses are in terms of deviation from the steady state level.

influences the households' consumption. As a result, we see a stronger consumption response to the negative terms-of-trade shock.

In response to the import shock, the fixed emissions level in the cap-and-trade policy yields a smaller decline in output than in the no-policy case. This leads to a smaller decline in investment. Households dissave relatively less than in the no-policy case, leading to an increased interest rate compared to the no-policy case. This is driven by a stronger price effect on consumption relative to the no-policy case. In the emissions tax policy, which fixes the emissions price, the decline in output is relatively higher than in the cap-and-trade policy. Households respond by dissaving relatively more than the cap-and-trade policy, leading to a smaller increase in the interest rate. This means consumption is affected relatively less by the price effect under an emissions tax. In the intensity target ratio, the decline in output is relatively bigger than in the cap-and-trade and emissions tax policy but smaller than in the no-policy case. Households respond by disinvestment, which is relatively bigger than the cap-and-trade and emissions tax policy, leading to the smallest rise in interest rate. This means that under the intensity target the price effect has the smallest effect on consumption compared to the cap-and-trade and emissions tax.

Table 1.7 shows CVs under the terms-of-trade shock. Consumption has higher variation compared to the productivity shock. However, we do not see any significant difference in terms of which policy is to be pursued to reduce the terms of trade shock's severity on consumption and labor. The cap-and-trade policy consistently has the lowest CV for the economic variables, but the variations in terms of percentage change are very small in differences across the policy instruments, with the exception of investment and trade balance. The CVs of the investment and trade balance under the cap-and-trade is significantly lower compared to other policy instruments. This finding is in line with our intuition that the cap-and-trade policy has stronger price effects under the terms-of-trade shock. Therefore, the cap-and-trade policy is not different from the other two environmental policies in reducing the terms-of-trade shock, especially if consumption and labor are considered. However, the cap-and-trade policy does reduce the shock's intensity on investment and trade balance, meaning the policy instrument is effective in limiting imports and investment.

We also check the results' robustness by employing the shock of higher magnitude and higher persistency. As before, the higher magnitude and persistent shock magnifies the differences in variation across policy instruments. The results for 1.5 standard deviation shocks with 90% persistency level are shown in the appendix (Table A.3, in Figure A.3, and in A.4). We find similar results. The cap-and-trade policy has little effect on consumption and labor, and is equivalent to the other policy instruments. As explained above, the cap-and-trade reduces the shock's intensity on trade balance and investment.

Table 1.7: Variations Under the Terms of Trade Shock

Variables	No policy	Cap	Tax	Intensity Target
Consumption	2.20	2.19	2.20	2.20
Labor	0.52	0.51	0.52	0.52
Investment	1.39	1.24	1.39	1.35
Output	0.25	0.22	0.25	0.24
Emission	0.25	0.00	0.25	0.24
Trade balance	2.72	2.53	2.70	2.67

Note: The table shows the coefficient of variation under 1 standard deviation negative temporary shock to the terms of trade, which is employed using a positive shock to the relative price of consumption in the model. The coefficient of variation is the standard deviation divided by the theoretical mean level (in percentage points).

Correlated Shocks

In the introduction, we discuss the terms-of-trade shock considering the potential link of business cycles to the fluctuations in the terms of trade. As we noted, responses under the terms-of-trade shock are not different from productivity shock for key macroeconomic variables, but these shocks are seldom uncorrelated. Then we ask the following questions: What are the effects on macroeconomic dynamics across the selected environmental policy instruments if the two shocks are correlated? Is there any condition under which the correlated shocks have influence on the macroeconomic dynamics? To answer these questions, we now employ correlated shocks, instead of separate shocks, as follows:

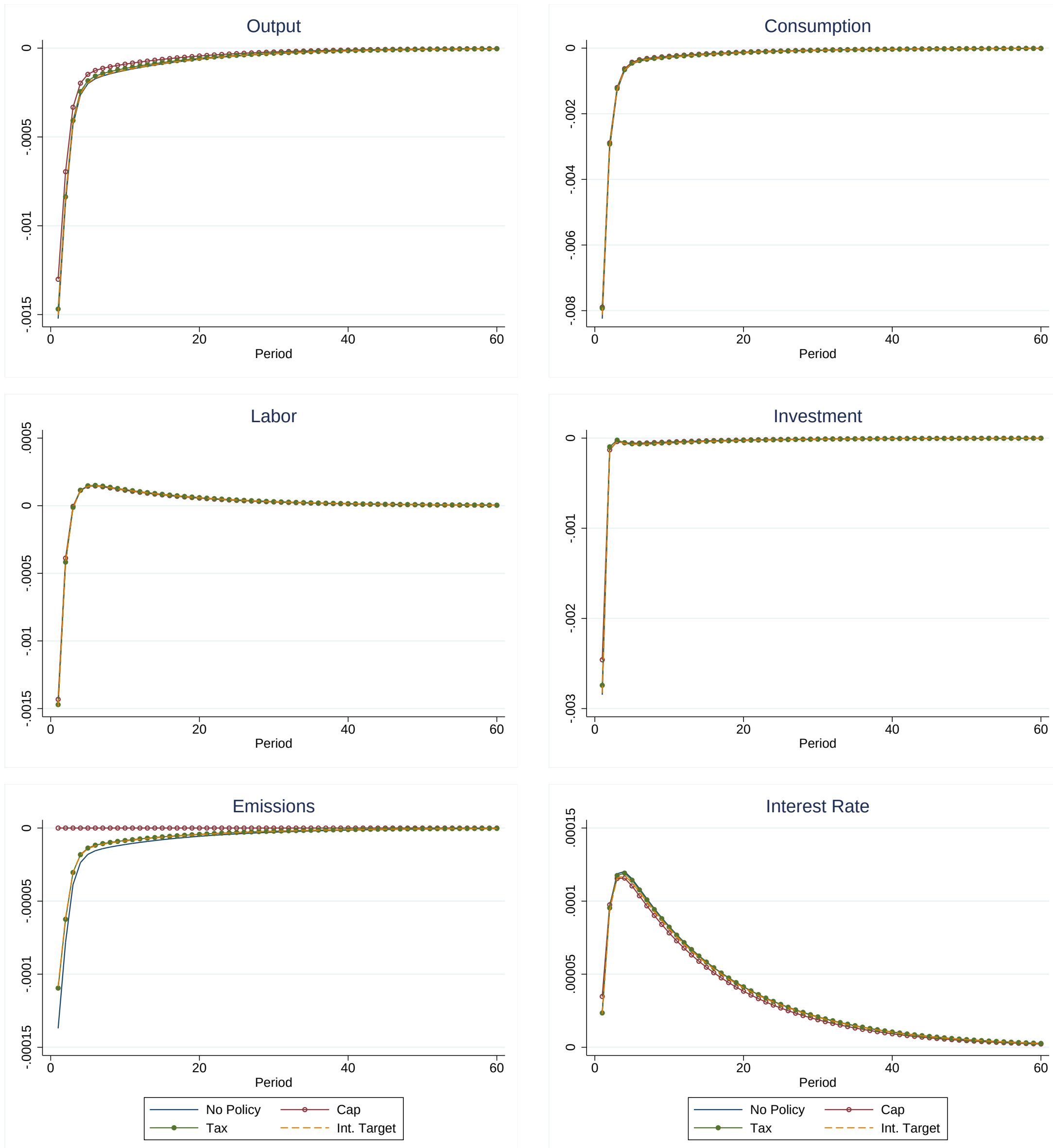

Figure 1.3: Impulse Responses Under the Terms of Trade Shock (Panel A)

Note: The figures show the impulse response functions of output, consumption, labor, capital, emissions, debt, current account, and trade balance in response to the terms of trade shock of one standard deviation by employing a positive shock to the relative price of consumption as shown on the bottom right corner panel in Figure 1.4. Zero on the vertical axis on each graph represents corresponding variable's steady state level. The responses are in terms of percentage deviation from the steady-state level.

$$\begin{bmatrix} \log A_t \\ \log p_t \end{bmatrix} = \begin{bmatrix} \rho_A & 0 \\ 0 & \rho_p \end{bmatrix} \begin{bmatrix} \log A_{t-1} \\ \log p_{t-1} \end{bmatrix} + \begin{bmatrix} 1 & \nu \\ \nu & 1 \end{bmatrix} \begin{bmatrix} \epsilon_{A_t} \\ \epsilon_{p_t} \end{bmatrix} \tag{1.27}$$

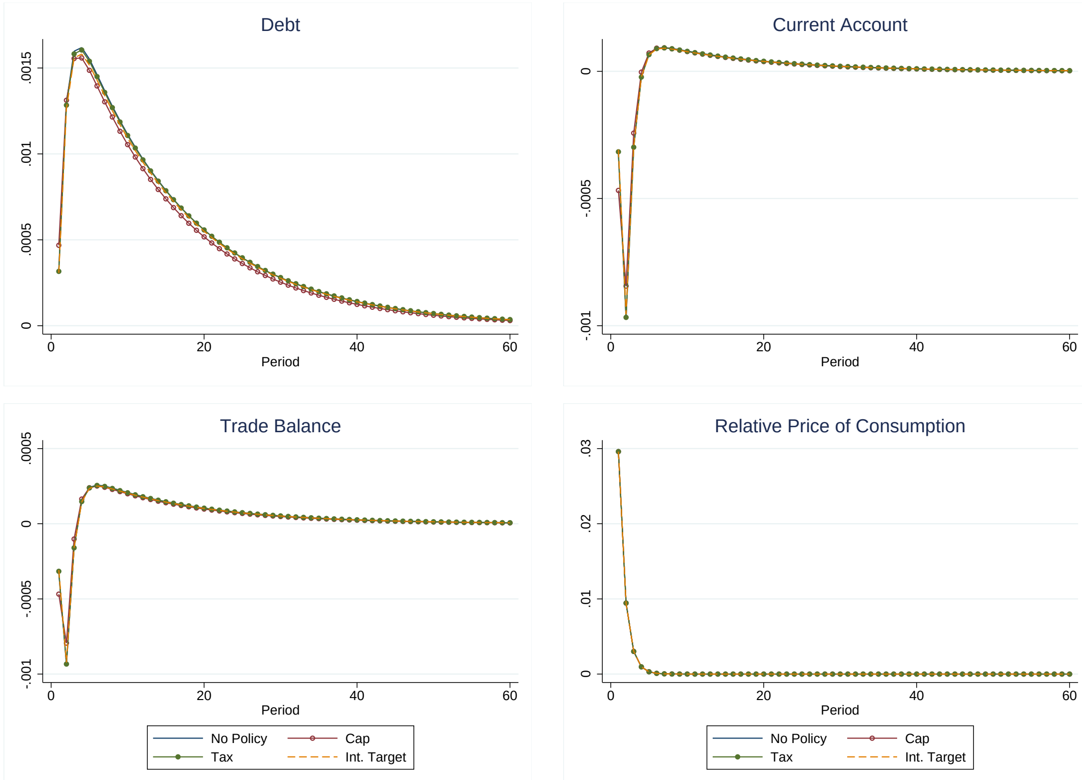

Figure 1.4: Impulse Responses Under the Terms of Trade Shock (Panel B)

Note: The figures show the impulse response functions of debt, current account, and trade balance in response to the terms of trade shock of one standard deviation by employing a positive shock to the relative price of consumption as shown on the bottom right corner panel. Zero on the vertical axis on each graph represents corresponding variable's steady state level. The responses are in terms of deviation from the steady state level.

where, $\nu = corr(\epsilon_{A_t}, \epsilon_{p_t})$ is the correlation parameter between the two shocks. Our estimation shows that the correlation between the two innovations as -0.0045.[17]

Table 1.8 shows the results under the correlated positive total factor productivity and negative terms-of-trade shocks.[18] The CVs are higher under the correlated shocks, but the results on smoothing the business cycles' intensity are similar to that under the productivity shocks. The cap-and-trade policy reduces the intensity of business

[17]The correlation is estimated using the two residual series from the univariate AR(1) process of the total factor productivity and terms of trade (hp-filtered with smoothing parameter 100).

[18]We also employ the productivity shock correlated with the terms-of-trade shock and separate terms-of-trade shock correlated with the productivity shock. In each case, the results are qualitatively similar to when faced with a separate shock. The separate shocks are more dominant than the correlated shock.

cycles' shocks, and this result holds under both positively and negatively correlated shocks. Therefore, the consumption smoothing under the terms-of-trade shocks fades away when these shocks are weakly correlated. However, we find that the correlation's degree and direction between the two shocks may influence the dynamic performance. The stronger the positive correlation across the two shocks, the more consumption smoothing occurs regardless of the environmental policy instruments, making those policy instruments equivalent in terms of variation on consumption. Table A.5 in the appendix shows the effects under higher correlations. We do not find such an effect on other variables, and their variations decrease under the cap-and-trade policy.

Table 1.8: Variations Under Correlated Shocks

Variables	No policy	Cap	Tax	Intensity Target
	$\nu = -0.0045$			
Consumption	2.28	2.25	2.28	2.28
Labor	1.25	1.11	1.25	1.23
Investment	10.46	9.01	10.65	10.30
Output	2.20	1.92	2.21	2.19
Emission	2.20	0.0	2.21	2.19
	$\nu = 0.0045$			
Consumption	2.28	2.24	2.28	2.28
Labor	1.24	1.11	1.25	1.23
Investment	10.45	9.00	10.64	10.29
Output	2.20	1.92	2.21	2.19
Emission	2.20	0.00	2.21	2.19

Note: The table shows the coefficient of variations under 1 standard deviation temporary correlated shocks of the terms of trade and total factor productivity. The coefficient of variation is the standard deviation divided by the theoretical mean level (in percentage points).

1.5 Welfare Cost

We follow the common practice in the emerging environmental macro literature and calculate welfare costs of environmental policy instruments. For each environmental policy instrument, we measure the reduction in consumption from the no-policy case, which would be necessary to make households indifferent between the no-policy case and the environmental policy cases. To do so, for each policy instrument, we calculate the discounted welfare's present value, keeping the supply of labor fixed at the steady-state level in the no-policy case. To ensure the consumption variable's response converges to the steady-state level, we choose 100 periods in the simulation.

Table 1.9 shows the changes in welfare cost across the policy cases as a difference from the welfare under the no-policy case.[19] Under the productivity shocks, the results show that the cap-and-trade policy has the highest welfare cost across the policy instruments while the intensity target has the lowest welfare cost; but the welfare cost difference is about 0.04 percentage point between cap-and-trade and tax policies, supporting the result in Fischer and Springborn (2011). However, under the terms-of-trade shock, the cap-and-trade's welfare cost is lower than the emissions tax policy by about 1 percentage point, making the two policies' welfare costs not significantly different. The intensity target has the lowest welfare cost irrespective of the shocks. The results also hold for highly persistent and higher magnitude shocks (See Table A.4 in appendix).

1.6 Conclusions

Policy makers are faced with a variety of instruments to limit pollution emissions. Among many important criteria such as cost effectiveness and political feasibility, emerging literature suggests that considering environmental policy's impact across the business cycle is also important. As countries become increasingly integrated into

[19]Note that the welfare cost does not include improvement in welfare from reduced emissions level under the environmental policy instruments.

Table 1.9: Welfare Differences Across Environmental Policy Instruments

Description	Change from No Policy				% Change from No Policy		
	No policy	Cap-and-Trade	Tax	Intensity Target	Cap-and-Trade	Tax	Intensity Target
	Productivity Shock						
Change in welfare		-0.5834	-0.5765	-0.1970	-3.19%	-3.15%	-1.08%
	Terms of Trade Shock						
Change in welfare		-0.5767	-0.5774	-0.1968	-3.14%	-3.15%	-1.07%

Note: The table shows the differences in welfare across environmental policy instruments from the no-policy case in response to productivity and terms of trade shocks of 1 standard deviation. In estimating the changes, total welfare is calculated as the sum of discounted utility, keeping the supply of labor fixed from the steady state under the no-policy case.

the world economy, the environmental policy's impact on trade flows has also become a consideration. To address these questions, we develop a DSGE model incorporating international trade and capital mobility. We then evaluate a pollution tax, a cap-and-trade policy, and an intensity target in response to the business cycles that may arise from uncertainty in the total factor productivity or the terms of trade.

We find that cap-and-trade reduces the business cycle's intensity caused by the productivity shock. However, we do not see a significant difference across environmental policy instruments if the terms of trade causes the business cycle, especially on key macroeconomic variables: consumption and labor. With an exception, under the terms-of-trade shock, the cap-and-trade is still the most effective policy instrument to reduce the trade flows' variation, meaning the policy is effective in limiting import surges. Our results show that the cap-and-trade policy strongly reduces the macroeconomic dynamics in response to environmental policies under productivity shock. These findings support the results of Fischer and Springborn (2011) and Annicchiarico and Dio (2015), but the results under the terms-of-trade shock differ from that of the literature. When these shocks are correlated, our results support the finding that the cap-and-trade policy reduces the business cycle's intensity. However, if the shocks are positively but highly correlated, then the variation on consumption across the environmental policy instruments are equivalent.

The welfare cost is the lowest under the intensity target, irrespective of the shocks. The cap-and-trade policy has a higher welfare cost than the emissions tax in the event of productivity shock, but the difference in the welfare cost between the cap-and-trade and emissions tax policies is small. In the event of the terms-of-trade shock, the welfare costs under the cap-and trade are lower than those of the emissions tax policies, but the difference is nearly indistinguishable. These results also hold for larger and highly persistent shocks.

Evaluating environmental policies' macroeconomic dynamics in an open-economy modeling framework that incorporates trade and capital flows is itself an important venture, which is also discussed in Fischer and Heutel (2013). We believe that our study represents a beginning with several possible extensions in the spirit of incorporating environmental policy into open-economy macroeconomic dynamic models.

Chapter 2

Emissions Leakage, Environmental Policy and Trade Frictions

2.1 Introduction

Unilateral changes in environmental policy in one region may cause countries with weaker environmental regulation to increase production of pollution-intensive goods. The associated increase in emissions in these regions is known as emissions leakage. The issue of carbon leakage has been a particular concern to policy makers because of the lack of global consensus on policies to reduce greenhouse gas emissions. Countries that have considered regulating emissions in the absence of coordinated global action have been concerned that production in polluting sectors would relocate to unregulated jurisdictions, thus reducing domestic employment without a corresponding reduction in pollution emissions.

In this study we develop a two-good, one-factor, small open-economy model with pollution emissions associated with one of the goods' production. We show that the level of leakage from a unilateral strengthening in environmental regulation depends on the level of trade frictions in the model. We present a special case of our model with free trade in the dirty good (which we term manufacturing), but the clean good (services) is not traded. We show that increases in the stringency of environmental regulation, which we model as a pollution tax, do not affect emissions in the rest of the world. In other words, unilateral environmental regulation is associated with zero emissions leakage when no trade is in the clean good.

This result demonstrates the importance of carefully modeling trade costs when evaluating emissions leakage's consequences from a unilateral change in environmental policy. In our model with no trade in services, an increased pollution tax causes a reduction in the relative price of services, but no corresponding change in the price of the polluting good relative to its world price. This leads to an equal reduction in domestic consumption and output of the polluting good and, thus, zero leakage. The consumption and production of services increase the same amount. When we model positive levels of trade in services, we find leakage consistent with the existing literature. We use the model to analytically decompose the changes' impact in the rest of the world's emissions after a unilateral strengthening of domestic environmental regulation in three distinct channels: income effect, output effect and terms-of-trade effect.

We find that the income effect causes negative leakage. Pollution tax increases lead to a reduction in consumers' real wages, thus reducing consumption. As a result, the exports of manufacturing goods increase, and the rest of the world's production decreases by a corresponding amount. Through the income effect, increases in the pollution tax lead to decreases in the rest of the world's emissions, if all else is equal.

The output and terms-of-trade effects cause positive leakage. Through the output effect, increased pollution tax leads to a decline in the manufacturing sector's production. This decline decreases the exports of manufacturing goods, and the rest of the world's production (and pollution emissions) increases to fill the gap. In the terms-of-trade effect, a pollution tax increase leads to a relative price increase, reducing the manufacturing sector's terms of trade. This reduction has two impacts on our model. First, exports of manufacturing goods decrease, and again foreign production and pollution emissions rise in response. Secondly, the relative price change also reduces domestic consumption of manufactured goods as households begin using services that increase exportation of manufacturing goods and that lead to declining production in the rest of the world. We show that the effect on production dominates the effect on consumption and that the net terms-of-trade effect causes positive leakage.

While we can analytically sign the leakage effects in the model, their relative magnitudes depend on parameters and initial values. To compare the effects' size, we calibrate our model to the Canadian economy. In simulations of services' trade costs taken from the literature, emissions leakage is 18% higher than when we simulate free trade in services. The simulations also demonstrate that among the channels in our model the terms-of-trade effect dominates. The income effect, which could be a source of negative leakage (decreasing the rest of the world's emissions) from an emissions tax increase is more than an order of magnitude smaller than the other two effects. For the chosen set of parameter values, we find positive leakage for all non-zero levels of the service sector's trade.

Two distinct methods are used in the literature to study leakage: analytical and computable general equilibrium (CGE) models. Among analytical models, recent studies have focused on identifying channels through which leakage operates and on exploring the potential for negative leakage. Karp (2013) develops a two-good (clean and dirty), two-factor, one-country model with both goods freely traded. The study decomposes emissions leakage into two effects: income effects and production effects. The reallocation of factors across the two sectors in his model because of an environmental policy causes the income and production effects. He argues that, if income effect is dominant, an increased environmental regulation may cause negative emissions leakage.

Modeling a two-good, two-factor, two-country framework, Baylis et al. (2014) shows that the emissions leakage depends on the two elasticities of substitution: the elasticity of substitution between the two-factor inputs in production, and the elasticity of substitution between the two commodities. The authors decompose leakage into the terms-of-trade effect (TOT) and the abatement resource effect (ARE).

An increased price of the home-country's good leads to positive leakage as consumers substitute with the other country's good (the terms-of-trade effect). Firms in the dirty sector substitute dirty inputs with clean inputs, leading to negative leakage (the abatement resource effect). In this study we focus on another potential avenue of lower emissions leakage estimates. We demonstrate that an increase in environmental regulation can be associated with less leakage if the service sector's trade costs are modeled directly.

Baylis et al. (2015) extends Baylis et al. (2014) to analytically decompose a CGE model's results into seven distinct leakage effects. We identify three analogous effects in our model: income, output, and terms of trade. We also find that income has negative effects and that output and terms of trade have positive effects on emissions leakage. Many of the effects in Baylis et al. (2015) do not appear in our model because of our focus on a small economy. Because our economy is a price taker, its environmental policy has no impact on world prices.[1] This assumption reduces the number of channels through which environmental policy (or trade costs) can affect emissions leakage, allowing us to focus on trade costs' impact on leakage from increased environmental regulation in the service sector. Because Baylis et al. (2015) (and Baylis et al. (2014)) focus on environmental policy, they do not address trade costs' emissions leakage impact in the service sector.

Trade costs in services represent a significant barrier to free trade. In addition to traditional tariffs, the service sector is exposed to a variety of non-tariff barriers. Professional services often face technical standards, licensing requirements, and language or cultural barriers that inhibit trade. Many personal services must be provided on location in real time (for example, haircuts, restaurants and construction) and are therefore untradeable.[2]

[1] For example, several researchers have modeled a "fuel price" effect, in which introducing environmental regulation reduces dirty fuels' global price. In these models the reduction in fuel price is one of the largest sources of leakage. We assume our economy's policy actions do not affect world prices, so this effect is not present in our model.

[2] Anderson et al. (2013) finds that trade barriers in services in Canada are much larger than trade barriers in goods. See Borchert et al. (2012) for more details on comparing service-trade restrictions

Most of the leakage literature has focused on trade in the polluting sector. While it is widely understood that in general equilibrium the linkage between the level of trade across sectors would affect leakage, this concept has not been widely studied. The impact that the clean sector's trade costs can have on emissions leakage has been largely overlooked.[3] We show that at lower levels of service-sector trade costs, a stricter environmental regulation is associated with less leakage for a service importer and more leakage for a service exporter.

Our small open-economy framework is new to the leakage literature, but it has been used in several studies that examine the relationship between trade and the environment.[4] One possible reason is that small open-economy models do not explicitly quantify emissions in the rest of the world. However, assuming that economies in the rest of the world are symmetric in emissions intensity but differ only by the environmental regulation's stringency, we show that the direction and the determinants for emissions leakage can be evaluated in a small open-economy model.[5]

While we use an analytical model to evaluate the impact of service sector's trade costs on leakage, our results also have implications for the many studies that investigate emissions leakage using a Computable General Equilibrium (CGE) framework. Paltsev (2001); Elliott et al. (2010a); Babiker (2005) each have developed multi-regional CGE models of the world to estimate a magnitude of leakage under an environmental regulation. These studies present net results and do not identify the effects of trade costs in services on emissions leakage. Typically, theoretical models assume trade costs in services to be zero, potentially because the costs are difficult to quantify across all the countries or regions modeled.[6]

across over 100 countries. See van der Marel and Ben (2013) for a discussion on different types of services' trade costs.

[3]See Hoel (1996) for a notable exception.

[4]See Copeland (1994) and Copeland and Taylor (2005) for examples.

[5]Different levels of emissions intensity between the domestic economy and that of the rest of the world would merely scale our results up or down depending on the difference's direction.

[6]Fugazza and Maur (2008) discusses the importance of modeling non-tariff barriers, which are a form of trade costs, in a CGE model. Walsh (2006) reviews the difficulties in estimating trade costs

CGE models that include services are calibrated to the realized trade flows in services. This calibration implicitly fixes trade costs in services at the level in the calibration data and implies the costs remain unchanged throughout the forecast period. These studies suggest that a unilateral increase in carbon taxes may increase emissions elsewhere in the world by as much as 10%-130% of the reductions in the country that imposes the tax. Our results suggest that a fall in trade costs in services could affect the estimated emissions leakage negatively (or positively) depending on whether an economy imports (or exports) services.

Several studies also explore the potential for negative leakage in a CGE model (see Elliott and Fullerton (2014); Baylis et al. (2013); Winchester and Rausch (2013); Carbone (2013)). They analyze leakage with respect to various levels of counterfactual elasticities across inputs and products in a CGE model. These studies find that elasticities of substitution in the production and utility functions affect leakage. The researchers also note little prospect of negative leakage (in a large multi-region model of the United States) because of the assumption of small fossil fuel supply elasticities. While our model is much simpler than these CGE models, incorporating a given level of trade cost in services allows us to introduce another dimension across which leakage may vary.[7]

The rest of this chapter is organized as follows. Section 2.2 outlines the model. Section 2.3 solves the model and evaluates the impact of a small increase in the emissions tax on leakage. To provide intuition, this section offers analytical solutions for the amount of leakage in two special cases: i) free trade in goods with completely non-traded services, and ii) free trade in goods and services. Then the marginal effects of trade cost in services on the emissions leakage are investigated, and a more general solution, showing how the amount of leakage varies with trade costs in the

in services. Neither of these studies focuses on the relationship between environmental policy and leakage.

[7]Many of the channels through which environmental regulation can affect the rest of the world's emissions in these CGE models do not exist in our model. Most importantly, the small open economy in our model is a price taker. Thus, it is difficult to predict how introducing trade costs into these models may affect the results as compared to our simple (and tractable) model.

service sector, is provided. Section 2.4 examines the relative magnitudes of leakage at different levels of service sector's trade costs by calibrating the model to the Canadian macroeconomic data. Section 2.5 concludes.

2.2 The Model

We model a small open economy with two representative sectors. A representative firm in each sector produces one good: manufacturing (x) and services (y). The manufacturing good is a composite good representing all goods that emit some level of carbon during their production process. The service good represents all outputs that do not emit any carbon during their production process.[8] Initially, we assume that manufacturing goods are freely traded internationally, but the service sector faces a trade friction, which represents the degree of trade costs in services. These trade costs may result from visa fees, required licenses or other professional standards, country-specific technical standards, legal hurdles, or differences in language and culture. In our model, we are agnostic about the types of barriers that cause these trade costs, but we model them generally as iceberg trade costs. Initially, we assume a fixed world price ratio for goods and services such that the economy exports manufacturing goods and imports services from the rest of the world.[9]

On the demand side, we assume a representative domestic household that consumes both manufactured goods and services to maximize utility. The household has access to international debt at a fixed (world) interest rate $\bar{R}$. The domestic government's role is limited to implementing an exogenous emissions tax per unit of emissions in the manufacturing sector and redistributing revenues collected to the households in a lump-sum transfer.[10] The balance of payment in the economy is unaffected by a change in environmental regulation.

[8]This classification is consistent with Levinson (2010), who finds that in the U.S. economy, services account for a tiny fraction of overall emissions.

[9]This assumption is convenient because our application simulates the Canadian economy and Canada is a service importer.

[10]For simplicity, we assume that the government maintains a balanced budget.

In both sectors, if domestic absorption is greater (less) than domestic production, the economy imports (exports) from (to) the rest of the world. Firms have the option to abate emissions or pay an emissions tax. Although mobile across sectors, labor is immobile across countries. For simplicity, we assume that population growth is zero. The parameters and policy variables are assumed such that an interior solution always exists for all decision variables.

We employ a constant relative risk aversion (CRRA) utility function with a constant elasticity of substitution (CES) aggregated over the consumption of goods and services.

The representative household's preferences are given by

$$U(c_x, c_y) = \frac{\left\{\left(\gamma^{\frac{1}{\rho}} {c_x}^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} {c_y}^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}}\right\}^{1-\sigma} - 1}{1-\sigma} - D\frac{S^{1+\sigma}-1}{1+\sigma} \tag{2.1}$$

where, c_x and c_y are consumption of manufacturing goods and services, respectively, $\gamma \in (0,1)$ is the weight in consumption of manufacturing goods, ρ is the constant elasticity of substitution between goods and services each period, and σ is the constant relative risk aversion parameter. We denote S as the stock of pollution emissions and $D \geq 0$ as the weight of dis-utility from pollution emissions. The stock of pollution emissions $S = e + e_{row}$, where e is the level of emissions and e_{row} is the level of emissions in the rest of the world. We assume that the representative household inelastically supplies her labor ($\bar{h}$) to firms (i.e. $h_x + h_y = \bar{h}$), where h_x is labor supply to the manufacturing sector and h_y is labor supply to the service sector. The emissions' stock is a negative externality that lowers utility but that has no effect on production.[11]

[11] Copeland (1994) and Angelopoulos et al. (2010) each models pollution's impact on consumers in a similar way

The household is subject to the following budget constraint

$$c_x + p\,\mu\,c_y + \bar{R}\bar{d} = w\bar{h} + \pi + G \tag{2.2}$$

where p is the fixed world relative price ratio of services to manufacturing goods and μ is the trade factor defined such that $p^d = p\,\mu$ represents domestic price. In a world with costless trade in services $\mu = 1$.[12] The amount of debt servicing is $\bar{R}\bar{d}$. The real wage per unit of labor supplied is w, and the real lump-sum transfer of tax revenues from the government to the household is represented by G. The manufacturing good is the numeraire with an assumed price of 1 so that all other prices can be interpreted as units of the manufacturing goods' price.

The representative household chooses c_x and c_y to maximize her utility (Eq. (2.1)) subject to her budget constraint (Eq. (2.2)). Using λ as the Lagrangian multiplier for the budget constraint, the household's maximization problem is represented by the following Lagrangian:

$$\max_{c_x, c_y} \mathscr{L} = \frac{\left\{\left(\gamma^{\frac{1}{\rho}} c_x^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} c_y^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}}\right\}^{1-\sigma} - 1}{1-\sigma} + \lambda\left\{w\bar{h} + G - c_x - p\,\mu\,c_y - \bar{R}\bar{d}\right\} \tag{2.3}$$

The first order conditions are

$$\left(\gamma^{\frac{1}{\rho}} c_x^{\frac{\rho-1}{\rho}} + (1-\gamma)^{\frac{1}{\rho}} c_y^{\frac{\rho-1}{\rho}}\right)^{\frac{1-\sigma\rho}{\rho-1}} \left(\frac{\gamma}{c_x}\right)^{\frac{1}{\rho}} = \lambda \tag{2.4}$$

$$\frac{C_x}{C_y} = \frac{\gamma}{1-\gamma}\left(\frac{1}{p\,\mu}\right)^{-\rho} \tag{2.5}$$

Eq. (2.4) ensures that the marginal utility from the consumption of goods is equal to the marginal utility of income. Eq. (2.5) shows that households' relative demand

[12] Note that μ can be defined as $\mu = 1 + f$ for service importers, where f is the iceberg trade cost in services. For service exporters, $\mu = \frac{1}{1+f}$. If services are exported, then the domestic price $p^d = \frac{p}{1+f}$. If services are imported, then the domestic relative price of services is $p^d = p(1+f)$.

of the two consumption goods depends upon the world relative price ratio p, μ, ρ and γ.

On the supply side, production in both sectors uses labor as the only input.[13] The production function in the manufacturing sector is $x = h_x^{\alpha_1}$, and the production function in the service sector is $y = h_y^{\alpha_2}$. The parameters $\alpha_1 \in (0,1)$ and $\alpha_2 \in (0,1)$ are the factor input elasticities in manufacturing goods and service outputs, respectively. Following Copeland and Taylor (2003b), we assume that the output production in the manufacturing sector (x) generates emissions (e) as the production's joint output.[14] Following Copeland and Taylor (2003b), we assume that firms have access to pollution abatement technology and spend a fraction (θ) of its output on the abatement process. Hence, the net output of manufacturing goods is $(1-\theta)x$, where θ is the fraction of gross output x used for the emissions abatement.

The structure of abatement technology in our model allows the firms to choose zero abatement if there is no emissions regulation or if the abatement is not cost effective. As in Copeland and Taylor (2003b), we use a specific abatement technology that models emissions as $e = (1-\theta)^{\frac{1}{\xi}}x$, where $0 \leq \theta \leq 1$ is the fraction of gross output (x) firms spend on abatement and ($0 > \xi > 1$) such that $e \leq x$. Here, ξ is the share of emissions expenditure in the net output of manufacturing goods. As ξ increases, abatement becomes less effective and more gross output is required to reduce emissions by the same amount. A non-zero level of emissions tax (T) is assumed to always exist in the economy, and the tax level is higher than ξ.[15]

The representative firm in each sector maximizes the following profit functions:

$$\max_{h_x, e} \pi_x = e^{\xi}(h_x^{\alpha_1})^{1-\xi} - wh_x - Te \tag{2.6}$$

[13]The labor factor can also be interpreted as a composite of capital and labor, or any arbitrary non-pollution inputs.

[14]This approach has been used in a series of influential general equilibrium trade and environment studies, including those of Copeland (1994) and Antweiler et al. (2001).

[15]We require this assumption since for any emissions tax level below ξ firms do not find it cost effective to abate emissions and, thus, choose to pay the tax. This abatement technology does not admit emissions taxes of 0. See Copeland and Taylor (2003b) for a full description.

$$\max_{h_y} \pi_y = p\,\mu\, h_y^{\alpha_2} - w h_y \tag{2.7}$$

The optimal conditions are

$$\alpha_1(1-\xi)\,\left(\frac{e}{x}\right)^{\xi} \frac{x}{h_x} = p\mu\alpha_2 \frac{y}{h_y} \tag{2.8}$$

$$\xi \left(\frac{x}{e}\right)^{1-\xi} = T \tag{2.9}$$

Firms employ labor (Eq. (2.8)) such that the marginal return to labor is equal across the two sectors.[16] Eq. (2.9) shows that firms optimally abate such that the marginal cost of abatement of emissions is equal to the per-unit emissions tax.

Plugging the firm's zero profit conditions into the budget constraint Eq. (2.2), the economy's resource constraint is thus

$$e^{\xi}(h_x^{\alpha_1})^{1-\xi} - c_x + p\,\mu\,(h_y^{\alpha_2} - c_y) = \bar{R}\bar{d} \tag{2.10}$$

The trade balance is then equal to the interest payments on the debt,[17] The transfer from the government to households is

$$G = T\,e \tag{2.11}$$

The trade flows in the manufacturing and service sectors are

$$b_x = e^{\xi}(h_x^{\alpha_1})^{1-\xi} - c_x \tag{2.12}$$

$$b_y = p\,\mu\,(h_y^{\alpha_2} - c_y) \tag{2.13}$$

where b_x and b_y are the trade flows in the economy's manufacturing and service sectors.

[16] Labor is mobile across sectors, but not across countries.

[17] thus allowing the country to run consistent trade deficits or surpluses in aggregate across the two industries.

In our model the emissions level in the rest of the world is not explicit since the model does not have an explicit production function of the rest of the world. We assume that a unilateral increase in pollution taxes would not alter the environmental regulation in the rest of the world. The rest of the world's consumption is not affected by a change in the level of domestic emissions tax since the world's relative price is fixed. The level of outputs in each sector in the rest of the world would vary depending on the changes in the trade flows in the corresponding sectors.[18] Hence, we define the change in trade flows in the manufacturing sector b_x as the "leakage" of emissions.[19] For an economy that imports manufacturing goods, an increase in imports suggests an increase in the rest of the world's emissions and thus leakage.[20]

2.3 Analytical Solution

In this section, we analytically solve the model through log-linearization. Taking logs of the first order equations and totally differentiating, the change in each variable is represented by a proportional change from its initial level (which we denote with $\hat{()}$). For example, a small change in x is indicated by $\hat{x} = \frac{dx}{x}$.

On the supply side, taking logs on both sides of Eq. (2.8) and totally differentiating yields

$$\xi \hat{e} + (1 - \xi)\hat{x} - \hat{h_x} = \hat{y} - \hat{h_y} \tag{2.14}$$

Taking logs on both sides of Eq. (2.9) and totally differentiating yields

$$\hat{e} = \hat{x} - \frac{1}{1 - \xi}\hat{T} \tag{2.15}$$

[18] The rest of the world is large compared to the small economy, thus implying that the change in the trade flows reflects the change in the emissions level in the rest of the world with respect to the emission level in the small economy.

[19] Alternatively, the emissions intensity in the rest of the world is assumed to be fixed, and the supply of manufacturing goods responds one-to-one to changes in domestic trade flows.

[20] If an economy exports manufacturing goods, then a reduction in exports implies leakage.

Log-linearization of the production functions yields

$$\hat{x} = \alpha_1 \hat{h_x} \tag{2.16}$$

$$\hat{y} = \alpha_2 \hat{h_y} \tag{2.17}$$

Also, from $h_x + h_y = \bar{h}$, we have

$$\theta_{hx}\hat{h_x} + \theta_{hy}\hat{h_y} = 0 \tag{2.18}$$

where θ_{hx} and θ_{hy} are the shares of labor in manufacturing and service sectors, respectively (hence, $\theta_{hx} + \theta_{hy} = 1$).

On the demand side, taking logs and totally differentiating both sides of Eq. (2.5) yield

$$\hat{c_x} = \hat{c_y} \tag{2.19}$$

The relative price ratio and trade friction are fixed. A percentage change in the demand for manufacturing goods must be equal to the percentage change in the demand of services. Unless there are changes in the relative price, the relative demand of each good will not change.

Totally differentiating the resource constraint in equilibrium (Eq. (2.10)) yields

$$c_x\hat{c_x} + p\ \mu\ c_y\hat{c_y} = e^{\xi}x^{1-\xi}[\xi\hat{e} + (1-\xi)\hat{x}] + p\ \mu\ y\ \hat{y} \tag{2.20}$$

We have a system of seven equations: optimal labor Eq. (2.14); optimal emissions Eq. (2.15); two production functions, Eq. (2.16) and Eq. (2.17); labor constraint Eq. (2.18); optimal relative consumption Eq. (2.19); and resource constraint Eq. (2.20). The system has seven unknowns: labor supply in the two sectors, $\hat{h_x}$ and $\hat{h_y}$; outputs in the two sectors, $\hat{x}$ and $\hat{y}$; emissions $\hat{e}$; and consumption of the two goods, $\hat{c_x}$ and $\hat{c_y}$. First, we solve for the change in amount of labor used in services $\hat{h_y}$

$$\hat{h_y} = \frac{\theta_{hx}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)} \frac{\xi}{1-\xi}\hat{T}; \tag{2.21}$$

and then, plugging $\hat{h_y}$, we solve for $\hat{h_x}$, $\hat{y}$, $\hat{x}$, and $\hat{e}$ (See appendix). Substituting these solutions in Eq. (2.20) and simplifying, the change in consumption expenditure on manufacturing goods ($\hat{c_x}$) is then

$$\hat{c_x} = \left[\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)} - S_x\right] \frac{\xi}{1-\xi}\hat{T}; \tag{2.22}$$

where, letting $C = c_x + p\ \mu\ c_y$ be the aggregate consumption, $S_x = \frac{e^{\xi}x^{1-\xi}}{C}$ and $S_y = \frac{p\,\mu\,y}{C}$ represent the shares of manufacturing goods and services in the aggregate consumption, respectively.

As shown in Eq. 2.22, a small increase in the emissions tax ($\hat{T}$) has two effects on consumption of manufacturing goods: an income effect and a terms of trade effect. The first term inside the bracket $\left[\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\right]$ is the income effect; and the second term $[S_x]$ is the price effect, which we refer to as the terms of trade effect.[21]

The third term outside the bracket is a scale factor $\left[\frac{\xi}{1-\xi}\right]$, the ratio of emission expenditure to potential output in the manufacturing sector, which we term as the abatement resource factor. This factor augments the income and terms-of-trade effects such that higher ξ increases the emissions tax's net effect on consumption as abatement becomes less effective. This factor's impact differs from other studies that have found an abatement resource effect leading to negative leakage. In those studies, the taxed sector substitutes clean resources shrinking output in other sectors, leading to negative leakage.[22]

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[21] These terms can also be rearranged such that $\hat{c_x} = \left[\frac{\alpha_2 S_y \theta_{hx}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)} - S_x\left(\frac{\alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)} + 1\right)\right] \frac{\xi}{1-\xi}\hat{T}$. In this case, the first term should be interpreted as the indirect effect and the second term as the direct effect of the emissions tax on consumption.

[22] Our model has only a single (clean) input and thus no scope for factor substitution. Polluting firms endogenously abates emissions by reducing output.

From Eq. (2.19) and (2.22), we note that a small increase in the emissions tax in a small open economy also has similar negative effects on consumption of services.

Proposition 1. *A small increase in the emissions tax in a small open economy has a negative effect on consumption of manufacturing goods because of the negative impact of both the income and the terms-of-trade effects.*

Proof: See appendix.

After an increased producer price in the manufacturing sector because of an increased emissions tax, income is affected through two channnels. First, the effective price of consumption is increased; thus, consumption of both goods and services decreases. Secondly, labor is reallocated to the service sector, reducing the real wage. This reduction reduces the real income available to consumers; and, as a result, consumption of manufacturing goods decreases. This effect is particularly important when we consider negative leakage. The more negative the income effect, the larger the increase in manufacturing goods' exports and thus the larger the leakage decreases.[23]

Corollary 1.1. *A small increase in emissions tax in a small open economy has a negative effect on consumption of services. The decline in consumption of services and manufacturing are proportional.*

Evident from Eq. (2.19), it implies that the emissions tax increase has negative effects on consumption of services, similar to the consumption of manufacturing goods.

Net imports are equal to consumption minus production in our model, $c_x - e^{\xi}x^{1-\xi}$. We define leakage as the rate of change in net imports and define it as $\hat{L}$ where $L = c_x - e^{\xi}x^{1-\xi}$. Hence, total differentiating L and plugging solutions for

[23] This finding is consistent with Baylis et al. (2015) who identify a "pure income effect" that reduces leakage. The pure income effect in that study arises from the assumption that tax revenue is spent on a public good rather than rebated.

change in consumption of manufacturing goods $\hat{c_x}$, emissions $\hat{e}$, and outputs in the manufacturing sector $\hat{x}$ with rearrangement yields the leakage

$$\begin{aligned}\hat{L} = \Bigg[& \frac{S_{cx}}{S_{mx}} \left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \\ & + \frac{S_x}{S_{mx}} \left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \\ & + \left(\frac{S_x}{S_{mx}} - \frac{S_x S_{cx}}{S_{mx}} \right) \Bigg] \frac{\xi}{1-\xi} \hat{T}\end{aligned} \tag{2.23}$$

where, $S_{mx} = \frac{b_x}{C}$ and $S_{cx} = \frac{c_x}{C}$ are the shares of manufacturing goods' exports and consumption in the aggregate consumption, respectively. Note that b_x is the trade flows in the manufacturing sector. $S_{cy} = \frac{c_y}{C}$ is the share of services' consumption in the aggregate consumption.

Proposition 2. *A small increase in an emissions tax in a small open economy has three leakage effects: income, output and terms of trade. The income effect is negative, and both output and terms of trade effects are positive. The net effect on leakage is positive.*

Proof:

As shown in Eq. (2.23), the first term $\left[\frac{S_{cx}}{S_{mx}} \left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) < 0\right]$ is the income effect. As noted in Proposition 1, this effect is negative, which increases exports of manufacturing goods and reduces leakage.

The second term $\left[\frac{S_x}{S_{mx}} \left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) > 0\right]$ is the output effect, which is positive. Outputs in the manufacturing sector decline because of increased input prices resulting from the emissions tax policy (See Eq. (2.16)). These increased prices decrease exports of manufacturing goods and lead to a positive leakage effect.

The third term on the right $\left[\frac{S_x}{S_{mx}} - \frac{S_x S_{cx}}{S_{mx}}\right]$ is the terms-of-trade effect, which has two components: effects on (1) consumption and (2) output of manufacturing goods because of the goods' increased relative price. The increased emissions tax increases the producer's price and worsens terms of trade in the manufacturing sector, thus decreasing the exports of manufacturing goods. As a result, a positive leakage effect which is shown by $\frac{S_x}{S_{mx}}$. As mentioned earlier, the increase in the producer's price also negatively affects consumption of goods, as households substitute goods with services. The substitution in consumption reduces leakage. This effect is shown by $-\frac{S_x S_{cx}}{S_{mx}}$. However, the output component dominates the consumption component, and the net effect is positive $\left[\frac{S_x S_{cy}}{S_{mx}}\right]$.

The scale factor $\left[\frac{\xi}{1-\xi} > 0\right]$ has the same effect as in Eq. (2.22). This factor describes how effective an environmental policy is at affecting the net emissions leakage. Furthermore, this factor has an economy-wide resource effect and increases with an increase in ξ (the share of abatement expenditure in output in the manufacturing sector). Abatement uses real output resources from the manufacturing sector. The lower the fraction of the manufacturing sector's output spent on abatement, the less effect the emissions tax has on leakage, as fewer resources will be spent on abatement.

We note that whether the economy imports or exports manufacturing goods, an increase in emissions tax yields emissions leakage.

2.3.1 Specific Cases

In this section we explore extreme cases of an economy with no trade in services (section 2.3.1) and costless trade in services (section 2.3.1) to better understand how the level of trade in the clean good affects leakage. Trade costs' general effects on emissions leakage is examined in section 2.3.1.

The case with freely traded goods and services assumes that the world's relative price is exogenous to the emissions tax change. In the case with no trade in services, the emissions tax affects the domestic relative price of services. Both of these cases make extreme assumptions about tradability of goods and services. However, the emissions tax change's impact on the relative price is an empirical question. Hoel (1996) argues that the relative price's immunity to the emissions tax change is not practical. On the other hand, Baylis et al. (2014) find a causal relationship between the change in the relative price and the negative leakage because of the abatement resource effect (ARE) present in their model. In our model, the case with no trade in services highlights the importance of change in relative prices by showing that emissions leakage is zero when relative prices do not adjust. The case with free trade in goods and services also highlights the relative importance of the channels through which an emissions tax change affects leakage.

No Trade in Services

We begin by considering an extreme case of an economy with no trade in services. In our model, no trade in services means zero trade balance in the service sector, which requires the following market clearing constraint

$$y = c_y \tag{2.24}$$

Then, the economy's trade balance is just the trade flows in the manufacturing sector. Manufacturing goods are exported; and the receipts are used to service international debt, balancing the capital and current accounts.[24]

Proposition 3. *In the two-sector small open economy with goods and services, if services are completely non-traded then a small increase in the emissions tax on pollution from the manufacturing sector leads to zero emissions leakage. The reduction in relative price of services proportionally decreases consumption and outputs of manufacturing goods, thus leading to zero emissions leakage.*

Proof:

Substituting Eq. (2.24) in the resource constraint Eq. (2.10), the economy's trade balance (which is also the manufacturing goods' export level) is

$$e^{\xi} x^{1-\xi} - c_x = \bar{R}\bar{d} \tag{2.25}$$

[24]In this way the economy can run a persistent trade surplus in the steady state.

Taking the log and total differentiating of both sides yields

$$s_x[\xi\hat{e} + (1-\xi)\hat{x}] - \hat{c_x} = 0 \tag{2.26}$$

where $s_x = \frac{e^{\xi}x^{1-\xi}}{c_x}$ is the share of output to consumption of goods in the manufacturing sector.

Since, in this case, the world relative price (p) is fixed and services are non-traded, the effective domestic relative price of services declines with an increased emissions tax. As a result of the decline, manufacturing goods' consumption declines in proportion with the decline in the manufacturing sector's output. In aggregate, the export level of manufacturing goods remains the same. The adjustment in the relative price of services affects both consumption and output proportionately, preventing emissions leakage.

The producer price increases in the manufacturing sector after an increase in the emissions tax. As a result, the effective relative price in the service sector decreases, and the relative demand for services increases. On the production side, labor is reallocated to the service sector. As a result, output in the service sector increases while output in the manufacturing sector declines. Hence, in this case, the increased emissions tax affects consumption and production in the service sector in the same direction, driven by the reduced domestic effective relative price in services. Also, the effects on consumption and production in the manufacturing goods' sector are balanced. As a result, this case yields zero emissions leakage.

Zero Trade Costs

We now turn to the other extreme case, an economy with zero trade costs in polluting manufacturing goods or clean services. Free trade in services ($\mu = 1$) ties domestic prices to world prices and re-introduces emissions leakage from the environmental policy. Total differentiation of the resource constraint in the long-run equilibrium

(Eq. (2.10)) yields

$$c_x \hat{c_x} + p\ c_y \hat{c_y} = e^{\xi} x^{1-\xi}[\xi \hat{e} + (1-\xi)\hat{x}] + p\ y\ \hat{y} \tag{2.27}$$

We have the system of seven equations: (Eq. (2.14), (2.15), (2.16), (2.17), (2.18), (2.19) and (2.27), and seven unknowns: $\hat{h_x}$, $\hat{h_y}$, $\hat{x}$, $\hat{y}$, $\hat{e}$, $\hat{c_x}$ and $\hat{c_y}$. Again, the system is first solved for the change in the amount of labor in the service sector $\hat{h_y}$

$$\hat{h_y} = \frac{\theta_{hx}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \frac{\xi}{1-\xi} \hat{T}; \tag{2.28}$$

and then, plugging $\hat{h_y}$ back in, we solve for $\hat{h_x}$, $\hat{y}$, $\hat{x}$, and $\hat{e}$ as before. Substituting these solutions in Eq. (2.27) and simplifying, the consumption expenditure on manufacturing goods ($\hat{c_x}$) is then

$$\hat{c_x} = \left[\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} - S_x \right] \frac{\xi}{1-\xi} \hat{T}; \tag{2.29}$$

where, $S_x = \frac{e^{\xi} x^{1-\xi}}{C}$ and $S_y = \frac{p\,y}{C}$ are the shares of manufacturing goods and services' output level in the aggregate consumption $C = c_x + p\ c_y$, respectively.

As before, letting net imports be the leakage level $L = c_x - e^{\xi} x^{1-\xi}$ totally differentiating L, plugging $\hat{c_x}$, $\hat{e}$ and $\hat{x}$ with rearrangement yields

$$\begin{aligned} \hat{L}_{free} = & \left[\frac{S_{cx}}{S_{mx}} \left(\frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \right. \\ & + \frac{S_x}{S_{mx}} \left(\frac{\alpha_1 \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \\ & \left. + \frac{S_x}{S_{mx}} S_{cy} \right] \frac{\xi}{1-\xi} \hat{T} \end{aligned} \tag{2.30}$$

where, $C = c_x + p\ c_y$, $S_x = \frac{e^{\xi} x^{1-\xi}}{C}$, $S_y = \frac{p\,y}{C}$, $S_{cx} = \frac{c_x}{C}$, $S_{cy} = \frac{c_y}{C}$ and $S_{mx} = \frac{b_x}{C}$. These shares are different from Eq. (2.23) since $\mu = 1$. This case has all three effects on emissions leakage, as in $\hat{L}$ in Eq. (2.23). The income effect is negative, and the output and terms-of-trade effects are positive with respect to emissions leakage from a change in environmental policy. In contrast to the case with no trade in services, the increased emissions tax affects consumption and production in the service sector in the opposite direction. However, the effects on consumption and production in the manufacturing sector are in the same direction. Because of the balance of payments constraint, the positive surplus in the service sector must balance with a deficit in the manufacturing sector. Thus, this case yields positive emissions leakage.

Effect of Service Trade Cost on Emissions Leakage

In this section, we explore how emissions leakage varies at different levels of the service sector's trade costs. Trade costs in services have generally decreased over time. Information technology has facilitated trade in services, and countries have been pressured to roll back services' trade restrictions (Miroudot and Shepherd, 2014; Gervais and Jensen, 2014). The special cases above suggest that the level of trade cost in services is crucial regarding the amount of leakage from changes in environmental policy. In this section, we show that a fall in trade costs in services affects emissions leakage.

We differentiate the emissions leakage $\hat{L}$ in Eq. (2.23) with respect to the trade friction (μ) to find the effect of changes in trade costs on emissions leakage from increased environmental regulation

$$\begin{aligned}\frac{\partial \hat{L}}{\partial \mu} = & \left[\frac{S_{cx}}{\mu\ S_{mx}} \left(\frac{\alpha_2 S_y S_{cx} \theta_{hx} + \alpha_1 S_x S_{cy} \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) \right. \\ & \left. + \left(\frac{S_x S_{cy}}{\mu\ S_{mx}} \right) \right] \frac{\xi}{1-\xi} \hat{T}\end{aligned} \tag{2.31}$$

where the first term, $\frac{S_{cx}}{\mu\ S_{mx}} \left(\frac{\alpha_2 S_y S_{cx} \theta_{hx} + \alpha_1 S_x S_{cy} \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \right) > 0$, is the change in the income effect as the service sector's trades increase. This effect suggests that the negative income effect from an increase in the level of environmental regulation is dampened in countries with high service-sector trade costs. The second term, $\left(\frac{S_x S_{cy}}{\mu\ S_{mx}} \right) > 0$, is the change in the terms-of-trade effect on emissions leakage, which is also positive. This effect suggests that the positive terms-of-trade effect from an increased level of environmental regulation on leakage is amplified by higher service sector trade costs. The fact that both effects are positive suggests increased level of environmental regulation has larger leakage effects in countries with high trade costs.

To explore this result's implications, we consider two countries, which are both service importers. One country has relatively high service-sector trade costs and the other relatively low. Both countries increase the level of environmental regulation by the same amount. Equation 2.23 shows that our model predicts leakage will increase in both countries. Equation 2.31 indicates that leakage will increase more in the country with high service sector trade costs.

In both countries the income effect on leakage from the increased environmental tax will be negative. Consumers will consume less of both goods and services after the environmental tax increase. This consumption decrease will lead to excess supply in the home country and more manufacturing exports, reducing the rest of the world's production and, thus, the rest of the world's emissions.[25] Equation 2.31 reveals that this effect will be dampened in the country with high trade cost. The relatively high price of services in the high trade cost country means that the loss in consumption associated with increased environmental tax will be smaller. The smaller the reduction in consumption, the lower the negative leakage associated with an increased environmental tax.

In both countries the terms-of-trade effect will be positive. An increased environmental tax will make the (imported) manufacturing good more expensive, thus leading to reduced manufacturing consumption, increased manufacturing production in the rest of the world, and increased pollution emissions. The country whose service sector's trade cost is high will find it relatively more expensive to substitute

[25] Also, a "pure income effect" results in which labor reallocation across sectors reduces wages and consumption.

manufactured goods with services after the price change. This will magnify the positive leakage effect in the country with high service sector trade costs.

In our model the service sector's trade costs have no impact on output, holding income, and terms-of-trade constant. Therefore, there is no difference in the output effect across the low and high service sector trade cost countries. The trade cost's reduction decreases only the nominal wage in both sectors, while the real wage remains the same. The nominal wage falls in proportion to the trade cost because price is defined relative to manufacturing goods' output price in our model. In other words, the domestic prices of services and manufacturing goods fall by the same proportion as the trade cost, for increased emissions tax. That means that the labor allocation will not change, and output in both sectors is constant.[26]

After rearranging Eq. (2.31), the equation can be rewritten as

$$\frac{\partial \hat{L}}{\partial \mu} = \frac{S_{cx}}{\mu} \hat{L} > 0 \tag{2.32}$$

where, $S_{cx} = \frac{c_x}{c_x + p\mu c_y}$. This leads to proposition 4.

Proposition 4. *Services' trade costs amplify emissions leakage. For service importers, increased environmental regulation is associated with more leakage when services' trade costs are high. If services are exported, a fall in trade costs in services increases the emissions leakage.*

The emissions leakage from a constant change in the level of emissions tax is affected by changes in consumption as a result of the income and terms-of-trade effects. For a fall in the trade costs in services, the sign of change in μ is negative when services are imported and positive when they are exported. Thus, the fall in trade costs in services decreases the income and terms-of-trade effects on emission leakage if services are imported and increases the income and terms-of-trade effects

[26] Also, differentiating manufacturing goods' output $\hat{x}$ and $\hat{e}$ (see appendix) with respect to μ shows no effect on these variables' changes. As expected, the change in output and, thus, the change in domestic emissions for a constant level of emissions tax should not change with μ.

on the emissions leakage if services are exported. The output effect, however, does not change with the trade friction's sign. Hence, if services are imported, the fall in trade cost in services has a negative effect on the emissions leakage; and if services are exported, a positive effect on emissions leakage results.

Corollary 4.1. *The marginal effect of a fall in trade cost in services on the emissions leakage is larger for a higher share of manufacturing goods in aggregate consumption, smaller μ, and higher emissions leakage from the emissions tax policy.*

The trade costs' marginal effect on emissions leakage depends on the existing trade costs' magnitude, the manufacturing goods' consumption share in aggregate consumption, and the magnitude of the emissions leakage itself. Evident from Eq. (2.32), the emissions leakage is affected by falling trade cost through income and terms-of-trade effects on the manufacturing goods' consumption. When services are imported, the relative price of domestic services decreases as services' trade costs fall, leading to decreased consumption of manufacturing goods at the margin. This decrease in manufacturing goods' consumption increases exports, if all else is equal, and thus reduces the terms-of- trade effect on emissions leakage. The larger the share of manufacturing goods' consumption in aggregate consumption, the larger the terms-of-trade effect on emissions leakage.

A fall in trade costs in services also increases households' real income, leading to increased manufacturing goods' consumption, thus reducing the income effect on emissions leakage. The marginal effect on the emissions leakage because of the income effect is higher if the initial μ is smaller, implying a bigger effective relative change in μ compared to its initial level.

2.4 Numerical Analysis

In the analytical solution, the effects on leakage depend on the initial equilibrium condition and the economy's deep structural parameters. Furthermore, in the analytical solution, the relative sizes of these effects are indistinguishable. In this section, we numerically estimate these effects by calibrating our model to macroeconomic data from Canada.

2.4.1 Data Aggregation and Calibration

We use long-run empirical relationships to identify our model's deep structural parameters. The model is calibrated such that the calibrated economy's structure can simulate the long-run equilibrium that matches the Canadian economy's historical annual data. The data on the historical annual expenditure-based GDP of Canada during 1981-2010 is available from Statistics Canada.[27] To be consistent with our model specification, GDP is imputed by netting out government expenditure and gross fixed-capital formations. The durable, semi-durable, and non-durable goods in the data are aggregated as manufacturing goods.[28]

During the period, manufacturing goods account for 53.1% of GDP and services account for the remaining 46.9%. Of the manufacturing goods 18.9% are exported (equivalent to 10.11% of GDP), and 2.2% of services are imported (equivalent to 1.0% of total GDP). Consumption of goods accounts for 43.3% of GDP while consumption of services accounts for 48.3%. The imputed debt-to-output ratio is 2.11.[29] We set $\bar{d} = 3.195$ and the total output in our model corresponds to Canadian \$ 668 billion, the average Canadian GDP during 1981-2010.

The parameter values used to calibrate the model's steady state to the Canadian economy are shown in Table 2.1. The share of consumption goods in the utility function (γ) is estimated by rearranging Eq. (2.5) and using the observed average consumption of goods and services. The average employee compensation in the Canadian economy's manufacturing and service sectors is 21% and 37% of gross

[27]Source: Statistics Canada. Table 380-0106 Gross domestic product.

[28]The definitions of durable and non-durable goods and services are in accordance with Statistic Canada's description. The services include transportation and storage, communication, finance, insurance, real estate, professional, educational, accommodation, and wholesale.

[29]The ratio is higher than the observed debt-to-GDP ratio because of the imputed GDP.

outputs respectively.[30] Labor share of manufacturing's and services' output is 0.21 and 0.37, respectively. The share of abatement expenditure in the manufacturing sector's output is assumed to be 9%, which is the level Fischer and Springborn (2011) used for the United States.[31] The exogenous international real interest rate is 4% per annum.

The services' trade cost is available from Anderson et al. (2013). The authors' estimate for the sample period (1997-2007) shows that the Canadian border is 1.63 tariff equivalent with the rest of the world .[32] The Canadian border's effect on services in the rest of the world ranges from the tariff equivalent of 23% in accommodations to 163% in wholesale services to 63% in aggregate services. Thus, we set the services' trade cost at 0.63 with $\mu(= 1 + \text{trade cost})$ as 1.63 in our model.

The world relative price of services (p) in terms of manufacturing goods is calibrated to match the empirical trade-flow shares of manufacturing goods and services to the imputed GDP. The export share of goods to the GDP in the calibrated economy is 10.11%, and the import share of services to GDP is 1.03%.

2.4.2 Results

We first solve the system of equations for the equilibrium with an exogenously fixed emissions tax. This emissions tax is arbitrarily set at 0.1, which is equivalent to 10% of the world price of manufacturing goods in our model. Then, we estimate the share of consumption, output, and both goods' and services' share of trade flows in aggregate consumption. These shares are then used to estimate the income, terms-of-trade, and output effects on emissions leakage. The sum of these effects is the total

[30]These shares are estimated over our sample period. Source: Statistics Canada. Table 383-0032 - Multifactor productivity, gross output, value-added, capital, labor, and intermediate inputs at a detailed industry level, by North American Industry Classification System (NAICS)

[31]Our estimate from the Canadian abatement expenditure data shows that the share is 7.5%, but data are only available for few irregular periods. Therefore, we follow Fischer and Springborn (2011). Using 7.5% does not materially affect the results.

[32]The estimate assumes that the elasticity of substitution is 6 across the following services in Canada: transportation, communication, wholesale, finance, business, education, health, accommodation, among others.

Table 2.1: Parameters in the Calibrated Economy

Parameter	Description	Value
	Deep structural parameters	
$\bar{R}$	Real interest rate	0.04
ξ	Share of abatement in output of goods	0.09
$\bar{h}$	Household's endowment of labor	1
γ	Share of goods in consumption	0.57
α_1	Labor share in goods	0.21
α_2	Labor share in services	0.37
μ	Trade friction$(1 + \text{trade cost})$	1.63
	Calibrated parameters	
σ	Intertemporal elasticity (risk parameter)	2
ρ	Elasticity of substitution between goods and services	2.2
p	World relative price of services in terms of goods	0.51
$\bar{d}$	Debt-level	3.195

effect of an increased environmental regulation on emissions leakage, which can also be treated as the "leakage multiplier" for a unit-percentage increase in the emissions tax. The leakage multiplier is a useful way to summarize the total emissions leakage resulting from the emissions tax change. Then the leakage multiplier is used to obtain the total emissions leakage for a unit-percentage emissions reduction.

Table 2.2 shows the calibrated trade-flow shares of goods and services to aggregate output. Also the shares of consumption of goods and services to the aggregate output in the Canadian economy are shown in the table. The economy's initial steady state is provided in Table 2.3.

The estimates for the three channels through which an increased pollution tax affects emissions leakage (income, output, and terms of trade) are provided in Table 2.4. The results indicate that the income effect is negative and small, while the output and terms-of-trade effects are positive and much larger. For these parameter values, the terms-of-trade effect comprises just over three-quarters of the total leakage from

Table 2.2: Empirical and Calibrated Data

Description	Empirical Data (1981-2010)	Calibrated Economy
Share of traded goods in GDP	10.11%	9.52%
Share of traded services in GDP	-1.03%	-1.08%
Share of consumption of goods in GDP	43.34%	43.56%
Share of consumption of services in GDP	48.26%	47.49%

Table 2.3: Initial Steady State in the Calibrated Economy

Variable	Value
Aggregate output(Y)	1.515
Output of goods(x)	0.804
Output of services($p\mu y$)	0.702
Consumption of goods(c_x)	0.660
Consumption of services($p\mu c_y$)	0.719
Labor in goods(h_x)	0.372
Labor in services(h_y)	0.628
Trade flows of goods(b_x)	0.144
Trade flows of services(b_y)	-0.016
Emissions(e)	0.0724
Emissions tax(T)	0.1

increased environmental regulation. The terms-of-trade effect accounts for the largest share of emissions leakage followed by the output effect. These effects dominate the income effect. As a result, the emissions leakage is positive.

We estimate that a 1% increase in the emissions tax in Canada will reduce domestic emissions by 1.12%. This reduction in Canadian emissions is associated with a 0.384% increase in the rest of the world's emissions. That generates leakage of 34.3%, meaning for every ton Canadians reduce their CO_2 emissions, the rest of the world's emissions increase by 0.343 tons and global emissions fall by 0.657 tons.[33] This emissions leakage estimate is comparable to estimates from similar policy counterfactuals for developed countries discussed in the existing literature. We are unaware of any policy experiment's estimates for Canada comparable to those presented here. Felder and Rutherford (1993) use a similar approach to estimate a policy counterfactual for OECD countries and finds 45% emissions leakage. More recently, Elliott et al. (2010b) estimates 40% emissions leakage for the United States.[34]

Table 2.4: Effects on the Emission Leakage Under Unit % Emissions Reduction

	Income	Output	Terms of Trade	Total Leakage
Leakage	-0.004	0.089	0.257	0.343
	(-1%)	(26%)	(75%)	

Note: The top row represents the effects on leakage, decomposed by channels for a 1% reduction in domestic emissions. The second row (in parentheses) shows each effect's share in the emissions leakage. The last column represents the total emissions leakage, which is the sum of the effects identified in our model. Emissions leakage is linear for small changes in the emission tax. The domestic emissions' reduction units are percentages of baseline Canadian emissions, and the emissions leakage units are a percentage of the unit % reduction in the domestic emissions. Therefore, 0.343 positive leakage implies that the rest of the world's emissions will increase by 0.343% if Canada reduces 1% of its emissions compared to its pre-policy change in emissions level.

Table 2.5 shows the differences in the estimates of emissions leakage, as a proportion of domestic emissions' reduction, for 1% reduction in domestic emissions under the three assumptions on the level of tradability in services: no trade in services, non-zero trade costs, and freely traded services. For non-traded services, the emissions leakage is zero. In our model with 63% trade cost in services, the total leakage is 34.3%. For zero trade cost in services, we estimate 27.9% emissions leakage. Zero trade cost in services lowers the emissions leakage by over 18%. Hence, the results

[33] This discussion assumes our small economy's emissions intensity is equal to the rest of the world's. If they differed, evaluating global (net) emissions reduction would require scaling the leakage by the difference in relative emissions intensity.

[34] Many CGE models estimate leakage, but tend to focus on leakage estimates' sensitivity to parameter choices or specific policies like the Kyoto Protocol rather than emissions policy's counterfactual analysis.

suggest that for Canada the emissions leakage from a stricter environmental regulation is positive, but a fall in the service sector's trade cost may lower emissions leakage.

Table 2.5: Effects of Trade Cost on the Emissions Leakage Under 1% Emissions Reduction

Cases	μ	Emissions Leakage
Non-traded services	∞	0
Trade cost in services with	1.63	34.3%
Zero trade cost in services	1	27.9%

Note: Each row represents the emissions leakage from a 1% reduction in domestic emissions at different trade cost levels in services. The emissions leakage is the change in the rest of the world's emissions in % of domestic emissions reduction. The top row represents the emissions leakage when services are completely non-traded. The second row represents the emissions leakage under the services' level of trade cost estimated from the literature. The third row represents the emissions leakage when the services' trade cost is zero.

2.5 Conclusion

In this study, we build an analytical general equilibrium model of a small open economy in which we include both freely traded polluting manufacturing goods and potential non-polluting services' trade costs. We decompose a small increase in pollution taxes' effects on emissions, known as emissions leakage, in the rest of the world. We extend the extensive literature on leakage from unilateral environmental regulation to show that the degree of tradability in non-polluting sectors greatly affects the amount of leakage. We also investigate the channels through which changes in environmental regulation affect emissions leakage.

When services are completely non-traded, we find that increases in environmental regulation lead to zero emissions leakage. The non-traded service sector's relative price will adjust to the new equilibrium. The global price of the polluting good, and thus global production and pollution emissions, will remain unchanged. The current literature typically assumes that services are freely traded and thus could misattribute leakage associated with services' trade costs.

In our model a stricter environmental policy leads to leakage through three channels: income, output, and terms-of-trade effects. The income effect negatively affects emissions leakage (i.e., increases in domestic pollution taxes reduce the rest of the world's emissions). The output and terms-of-trade effects lead to positive emissions leakage. Based on a model calibrated to the Canadian economy, our results suggest that the output and terms-of-trade effects dominate the income effect; thus, there is positive net emissions leakage. Our results suggest that with a stricter emissions tax, a 1% reduction in domestic emissions yields an emissions leakage of 34.3%, reducing global emissions by 0.66 ton for each ton of domestic reduction. Furthermore, we find over 18% lower emissions leakage if services' trade costs fall from the level estimated in the literature (63%) to zero.

In this study, we employ a small open-economy framework to simplify our model and derive analytical results for the three channels of leakage. The small economy assumption means that some channels (for example, fuel-price effect) identified elsewhere in the literature through which leakage can occur are not present in our model. Future work should address whether -and if, how -the assumption of no, or constant, trade costs in services affect estimated emissions leakage in large-scale CGE models.

Chapter 3

Output Multipliers and State Rainy Day Funds

3.1 Introduction

In the early 1980s during the recession, states were under pressure to reduce spending and raise taxes because of falling revenues. These responses led to several states establishing formal budget stabilization funds popularly known in the U.S. as "rainy day funds" (RDFs). The funds were seen as a mechanism to smooth taxes and spending to alleviate fiscal stress during the recession. Nearly all the states in the U.S. have adopted these funds. However, little empirical evidence exists regarding the impact of RDFs on state economies.

While the intent of RDFs is to smooth taxes and expenditures, the states' uncoordinated behavior may impart a fiscal externality on the macroeconomy that helps smooth the business cycle. While specific rules vary by state and have evolved over time, fund accumulation removes purchasing power from the economy during periods of economic expansion and injects stimulus into the economy when funds are disbursed during periods of economic stress. The states' collective behavior may yield measurably important impacts for macroeconomic performance. Understanding the magnitude of these impacts is important for central government policymakers in designing and implementing countercyclical policies.

Fiscal policy's impact on output is of longstanding interest and has been extensively studied in the literature, though little research has examined state-government policy's role. To estimate output multipliers, recent literature has explored fiscal stimulus through the American Recovery and Reinvestment Act (ARRA) (Feyrer and Sacerdote, 2011; Wilson, 2012) and through federal military spending (Barro and Redlick, 2011; Ramey, 2011). Some researchers have used innovative forms of exogenous variation to identify the output multiplier. For example, Romer and Romer (2010) identify the fiscal multiplier using exogenous changes in federal taxes and Shoag (2013) uses variation in state pension spending. Sheremirov and Spirovska (2015) find that the government expenditure's output multiplier would be large if government expenditure is debt financed or even larger than one if monetary policy is accommodative. Recently, Nakamura and Steinsson (2014) identify the open-economy multiplier using state-level variation in U.S. military spending. The authors find a small output multiplier, which is larger during recessions consistent with greater slack in the economy. Clemens and Miran (2012) exploit the state-level variation in balanced budget rules as an identification strategy. These studies suggest that government spending has a significant stimulus impact on states' outputs. Considering funds accumulated in a RDF as a savings account, this may have consequences on states' economies. In this study, we provide evidence of such consequences in the case of RDFs.

RDFs have become an integral part of states' fiscal institutions and serve as a formal budget stabilization tool. In contrast to the other forms of policy variation considered in the literature, RDFs generate policy variation in how states respond to fiscal stress and potential budget imbalance. The variation in states' responses to unexpected deficits or surplus is an alternative mechanism for capturing the fiscal multiplier. The mechanisms states use to deposit or withdraw from RDFs vary widely. These mechanisms evolve over time (Bailey et al., 2014; Rose, 2008). Some states use state legislative appropriation; in more than half of the states, some percentage of year-end surplus (for example, such as 5% of the general fund's balance) is specified to be deposited into RDFs. Some states use stricter rules involving formulas for deposits and withdrawals (Bailey et al., 2014; Rose and Smith, 2011; Hou, 2013, 2004).

Several studies examine whether the RDFs' balances represent real savings (See Gonzalez and Levinson (2003); Hou (2004); Hou and Duncombe (2008), and Knight and Levinson (1999)). The issue is whether RDFs simply account for other idle balances that states might hold. One approach is to compare the differences in the general fund's balances with the RDF. Our examination of RDFs takes a different path by exploring whether fund accumulation and disbursement have measurable effects on state and national economic performance. If RDFs represent real savings, there should be statistically significant effects on metrics, such as gross domestic product (GDP).

The impact of fiscal policy on output and its components has long been a central part of the literature on fiscal multipliers. Likewise, the central debate in the public finance literature evaluating RDFs is whether they reduce fiscal stress during economic downturns. The debate over the RDFs' ability to reduce fiscal stress is ongoing. At the same time, no empirical evidence is available on how the RDF's provision affects economic performance generally and over the business cycle particularly. To the extent that a RDF's disbursement leads to economic stimulus, an additional mechanism reduces fiscal stress. This is the central question addressed in this study. We use two separate strands of literature: the macroeconomic fiscal multiplier literature and the state budget stabilization literature to quantify RDFs' impact on state output.

Our study also speaks to the important question of fiscal policy coordination within a monetary union. The federal government and the states have extensive control over tax and spending instruments. However, the question of fiscal policy coordination across levels of government in the U.S. has largely been ignored since the Great Depression. In the years following the depression, Hansen and Perloff coined the term “fiscal perversity hypothesis” to explain the states’ procyclical behavior. It was recognized that the states were required to maintain balanced budgets; in practice, state fiscal policy may have deepened the depression through tax increases and spending cuts. More recent federal fiscal stimulus during the Great Recession was intended to help offset potentially the states’ contractionary budget actions. To reduce the states’ propensity to reduce spending, hold harmless provisions were put in place for some spending categories. The states do not use RDFs to affect economic growth, yet these funds may have this effect. Federal fiscal and monetary authorities need to know the nature of state RDFs’ countercyclical influences to properly design and evaluate central government’s actions. We believe our study helps to highlight the importance of state-level countercyclical fiscal policy in stabilizing the economy.

The key questions addressed in this study are the following:

- What are the impacts of RDFs on state output?
- What is the differential effect of RDFs during expansions and contractions?
- Do RDFs during election years have any impact on state outputs?

To empirically assess these questions, we use a panel of data for 43 U.S. states for the sample period 1987-2010. We use an Arellano-Bond estimator and control for the effects of any general fund surplus in our specification. Our findings suggest that the average output multiplier of RDFs is about 1.5. During recessions, the multiplier increases to about 3.4. Our assessment shows that RDFs in election years have impacts on state outputs as big as in recessionary periods. This suggests that RDFs are used in part for political purposes.

By identifying RDFs’ effects on economic growth, our findings offer strong evidence that RDFs constitute genuine savings on the part of the states. The growing role of RDFs in state finances also suggests the need for coordinating monetary and fiscal policies across federal and state governments. Finally, our results may be useful to monetary unions such as the EU, whose member countries maintain budget-stabilization funds in the absence of central government’s fiscal authority.

In section 3.2, we review relevant literature on RDFs. Section 3.3 briefly explains the rules governing RDFs and their evolution over time. In section 3.4, we describe the compilation and source of data used as well as the methods, identification strategy, model specification, and results. Section 3.5 provides a conclusion.

3.2 Literature Review

The existing literature on budget stabilization funds, known as "rainy day funds" (RDFs), mainly focuses on three questions: i) Do RDFs affect states' savings behavior, meaning do RDFs increase state general fund balance? ii) Does the provision of budget stabilization funds reduce fiscal stress (i.e., Does a RDF have any role in smoothing government expenditure over the business cycle?) and iii) What is the optimal size of budget stabilization funds, for example, are fund sizes adequate to alleviate fiscal stress? Addressing these questions will help in understanding the potential role of RDFs as a countercyclical stabilizer.

Effects on State Savings Behavior

Historically, states have long used general fund surpluses (GFSs) as a reserve to absorb revenue shocks. The GFS may also have countercyclical influences on the economy. The fund accounts for the general fund's unreserved and undesignated balances (UUB) that are usually referred to as the general fund surplus (Hou, 2013). The GFS is a part of state government's operating fund; thus, it is designed to operate within a fiscal year. Unlike the GFS, states establish RDFs as a formal budgeting tool subject to legislative oversight that prescribes the funding and disbursing process during boom and bust years. This process is important since RDFs in principle operate over the long term, including entire economic cycles. In contrast to RDFs, the GFS is often under contemporaneous spending pressure and is not structured to provide funding across fiscal years. In the process of identifying the impact of RDFs, a substitution effect may result across the two funds if one is used in lieu of the other; complementarity may arise if both funds are increased simultaneously or decreased simultaneously. Wagner (2003) and Hou (2004) find strong evidence that stabilization funds are substitutes for a general fund balance. If two states face a similar fiscal shock during an economic downturn, one state may use its GFS balance to offset pressures to increase tax or reduce expenditures while another state might use a RDF. Our empirical application controls for GFS's effects when examining the budget stabilization fund's impact on state outputs. Since the GFS operates within a fiscal year, we expect any effect on growth to be modest.

Knight and Levinson (1999) examine the effect of RDFs on state savings' behavior. Their finding is that states with RDFs have higher general fund balances compared to those states without RDFs. States with a higher cap in the RDF and stricter rules for withdrawing, such as withdrawal only during an economic downturn, lead to higher balances. The question is whether RDFs represent net savings or are simply a different way of accounting for idle balances. Importantly, they conclude that RDFs do represent savings; this finding is important for our work.

Using panel data for the US states for 1974-1997, Wagner (2003) finds that a general fund's balance and RDFs' balances are substitutable to some extent. In contrast to Knight and Levinson (1999), they find that the RDFs' role on smoothing the income shock may be limited since a dollar in a RDF deposit reduces the state governments' budget surpluses by about 51 to 56 cents. This finding is important, and we control for the effects of GFS in our work.

On the other hand, Hou and Duncombe (2008) show that characteristics of the balanced budget requirements (BBR) and the RDF play a major role in states' saving behavior. The authors use panel data collected from financial statements with a sample period (1979-2003), which includes three important recessions and three business cycles. Their findings suggest that merely appropriating RDFs from the general fund balance would not increase the total savings as Wagner (2003) also noted. Importantly, however, the authors suggest that the characteristics of BBR and RDFs are essential to increasing state savings. For example, RDFs with a higher balance cap increases state savings, as Knight and Levinson (1999) also note. Likewise, a relatively restrictive BBR such as "no deficit carry-over to the next fiscal year" may increase state savings.

McGranahan (2002) and Zahradnik and Ribeiro (2003) find that RDFs help states' weather recessions, but these authors remark that an appropriate configuration like higher caps, flexible rules to use fund during economic downturn, and removal of replenishment rules could significantly improve RDF's effectiveness. Gonzalez and Paqueo (2003) conclude that funds ruled by stringent requirements accumulate higher balances and reduce social sector expenditure volatility. Knight and Levinson (2000) and Wagner (2003) find evidence suggesting that states with funds operating under strict rules save more and receive better bond ratings, making future borrowing less costly for the state. Importantly, these studies show that rules matter for RDFs' effectiveness.

In a more recent study, Wagner and Elder (2005) investigate RDFs' effects on states' credit ratings, bond yields, and borrowing costs. Because of RDFs' ability to improve states' ability to cope with economic downturns and to reduce the risk of default, the funds should decrease the state's cost of borrowing. The authors find evidence that the borrowing cost is reduced in states that adopt RDFs with rules for deposit and withdrawal compared to the states that adopt RDFs without such rules. The study externally validates that RDFs constitute savings.

To our knowledge, Navin and Navin (1994) study is the only one investigating the relationship between the RDF's balance over time and state economic indicators: gross state products (GSP). However, their analysis is highly descriptive and relies only on correlation analysis. The authors examine the changes in the RDF's balance between 1983 and 1991 to evaluate fiscal health in seven Midwestern states. The authors use simple correlation coefficients between the RDF's balance and the economic indicators' pre- and post-stabilization period (1983-1991), and they also use mean and variance analysis. Their results show that the use of RDF varies significantly among states; thus, the effectiveness of RDFs also varies among states.

Ability to Reduce Fiscal Volatility

If RDFs can affect fiscal stability, the likelihood increases that they can have a meaningful impact on the economy. Wagner and Elder (2005) examine how state expenditure's volatility is affected by stabilization funds' size and structure using data from 1969 to 1999, including the RDF's entire history of use. Their findings suggest that, although the "average" state has not witnessed reduced expenditure volatility by using a RDF, rules governing RDFs matter in reducing such volatility. They find that states following RDF rules have less volatility in their expenditure than states that do not have such rules. If governed by stricter deposit and withdrawal rules (i.e., requiring deposits or limiting withdrawals), stabilization funds have significant effects on reducing expenditure volatility.

Douglas and Gaddie (2002) and Sobel and Holcombe (1996) examine the degree to which RDFs eased "fiscal stress" during 1990-1991 recession. They define fiscal stress as the sum of discretionary expenditure reductions and tax increases from 1989 to 1992. Their finding suggests that a strict deposit rule eases fiscal stress, providing evidence that RDFs played a role in smoothing the fiscal cycle in the 1990-1991 recession. Multiple contingency funds along with savings requirements are the key factors affecting fiscal stress regardless of RDF sizes.

Gonzalez and Paqueo (2003) examine RDFs' effectiveness in reducing the volatility of social and nonsocial sector expenditures. They find that RDFs are ineffective in reducing the volatility of the nonsocial sector's expenditures but are effective in reducing the volatility of the social sector's expenditures. They also find that states with stringent deposit and withdrawal rules have higher RDF balances and, thus, are more effective in reducing the volatility of the social sector's expenditures.

Optimal Design of Budget Stabilization Fund

Over the years as RDFs have been adopted, states have yet to answer the single-most important question: What is the RDF's optimal size? A larger RDF means a larger opportunity cost in terms of foregone private sector and public sector consumption. On the other hand, a smaller RDF may not be adequate to cope with fiscal stress when facing a typical downturn. With this kind of trade-off, a general rule of thumb of a RDF size of five percent of general fund expenditure emerged as a norm. However, several studies provide evidence arguing against such a rule. Joyce (2001) uses a composite volatility index to compare state budget volatility with RDF size. He argues that the RDF's size should depend on state budget characteristics that contribute to state economic volatility and that these characteristics widely vary among the states. He does not find the rule of thumb fits all states. Also, in a study specific to Ohio, using historical personal-income data and revenue forecasting, Navin and Navin (1997) argue that such a rule of thumb is inadequate and suggest a target of about 13% of the general fund's expenditure. Zhao (2014) and Mattoon (2003) suggest that the existing caps on RDFs in several states are not adequate and that states often do not have sufficient reserves in their RDFs to cope with fiscal stress during economic downturns.

In a recent study, Tejedo (2012) uses panel data from 1951 to 2000, dropping the observations after the states adopt a RDF, to investigate the determinants of choosing a RDF's configuration after states adopt RDFs. Her main findings are that the states with higher debt levels may establish weak deposit requirements but stricter withdrawal rules. Furthermore, fiscal characteristics, such as levels of tax effort or volatility of state spending, are important factors that determine the choice of a RDF's configuration. On a similar note, Wagner and Sobel (2006) also find evidence that some RDFs were adopted to circumvent existing fiscal constraints, such as tax and expenditure limits. Rose (2008) examines how states use the funds and finds evidence of fund manipulation during an election year. She finds that states withdraw as much as three times more funds in response to deficit shocks occurring in election years than those in non-election years. In our empirical application, we consider use of a RDF during an election year.

3.3 RDF Deposit and Withdrawal Rules

Our initial identification assumptions are that the changes in RDFs are affected by the variation in rules for deposit and withdrawal over time and that these rules vary across states but are not correlated to exogenous shocks. Such changes in RDFs are predetermined as states determine how much to deposit in or withdraw from RDFs based on how much money they have left at the end of the fiscal year. Our strategy of using the changes in RDF balance can also be justified by the variation in changes in RDFs within states, which is much higher than the variation across states. The states also adjust rules for deposit and withdrawal over time, giving an additional source of exogenous variation. We describe the deposit and withdrawal rules across the states in the following subsection. In the appendix, we provide the rules for 48 states in 2002 and 2008, and the changes in the rules are highlighted to show their evolution over time.

Deposit Rules

States deposit funds in RDFs using four methods: i) discretionary transfer from general fund surplus based on year-end revenue, ii) legislative appropriation from the general fund, iii) use of a predetermined formula from the general fund, and iv) special revenues. Most states cap the amount of deposits, and these caps vary widely from 5% of the general fund in Idaho to 12% of the general fund in the immediately preceding fiscal year in Maine. Some states do not have limits for deposits. The caps increased in several states during 2002-2008, indicating a growing interest in fiscal stabilization. Several states use stringent deposit rules, such as predetermined formula. For example, Virginia uses a deposit formula that uses the average revenue growth over the preceding six years as a trend to deposit automatically into the RDF 50% of the surplus revenue above the trend (Bailey et al., 2014). Ohio and Indiana use personal income's growth rates (Navin and Navin, 1997); Michigan uses revenue's annual growth rate (Hou, 2004). In Maine, the deposit has to be at least one percent of the general fund revenue. Nearly 21 states determine how much to deposit based on the surplus at the end of the fiscal year (Bailey et al., 2014). States like California, Arkansas, Wyoming, and Missouri deposit monies in their RDFs by legislative approval, leaving the decision to save to the lawmakers' discretion. States like Alaska and Louisiana use special revenues, such as oil and gas rents or settlements, for deposits in their RDFs.

Withdraw Rules

States withdraw monies from their RDFs based on three methods: i) executive discretion, ii) predetermined formula, and iii) legislative appropriation. A governor's declaration of emergency can provide open access to RDFs in states like Florida, Oklahoma, Pennsylvania, and Minnesota. These decisions are formalized by legislative vote. Some states use automatic procedures to withdraw money from the fund involving formulas, which restrict the procedure to economic conditions rather than to politicians' discretion. Such formulas are used in Arizona, Michigan, Indiana and North Dakota (Hou, 2004). To withdraw funds, several states employ a stringent method that requires legislative approval. In Illinois, withdrawal from the RDF has a strict repayment provision, requiring all withdrawals from the fund to be repaid in full within the fiscal year. Such a restrictive method limits the capacity to provide fiscal stabilization and limits the impacts on states' economic growth.

Although it is beyond this study's scope to describe or model the rules in each state, it is evident that the states' methods for deposit and withdrawal may have different effects on state outputs. The stricter the formulary rules for deposit, the higher the RDF balance is. On the other hand, the more restrictive it is to withdraw from the RDF, as with states requiring legislative approval, the higher the RDF's balance will be. In contrast, the less restrictive the rules are for deposit (like appropriating fund transfers) and the less restrictive the rules are to withdraw from the RDF (like using a formula), the lower the fund's balance will be. These rules affecting changes in RDF may in turn have differing impacts on state outputs.

3.4 Estimating the Rainy Day Fund Output Multiplier

In this section, we discuss our empirical strategy for estimating state-level RDFs' output multipliers. We compile annual data on states; Gross Domestic Product (GDP), budget stabilization funds, and other state-level economic activity for the American states during 1987-2010. Our measure of output is state-level GDP that the U.S. Bureau of Economic Analysis (BEA) constructs. From the U.S. Census Bureau we obtain state population and unemployment rate data (Table 3.1). We use GDP deflators based on two time series of chained GDP: 1987-1997 at 1997 US$ and 1998-2010 at 2009 US$, available at BEA. The later series is converted to 1997 US $ to calculate state-level GDP deflators. Table 3.2 summarizes statistics of the data in level, and Table 3.3 presents the data in one-period changes.

Our dependent variable is the one period ahead of change in state GDP, and the primary explanatory variable is the one period of change in the RDF balance. We also have data for an alternative measure of budget stabilization funds: the general fund surplus (GFS).[1] We select the sample period (1987-2010) to exploit rich data on both the number of states and the use of RDFs. The sample period also includes three recessions: 1990-1991, 2001, and 2007-2009. By 1990, 39 states had adopted a formal RDF; and by 2010 all states had adopted a formal RDF except Kansas and Montana. We drop seven states: Alaska, Washington, Alabama, Arizona, New Mexico, Montana and Kansas. Alaska is an outlier that has a disproportionate level of RDF balance compared to other states. The fund's major source in Alaska is oil rent, and the fund's balance is highly affected by oil prices. The data for Washington are incomplete. Alabama, Arizona, New Mexico and Arkansas are also dropped because the balances were zero throughout the sample period. Montana and Kansas are

[1] The data are drawn from Hou (2013). Each series was compiled using various sources including Comprehensive Annual Financial Reports (CAFR). Some states do not report their RDFs in CAFR.

dropped because of a RDF's non-existence. Figure 3.1 shows the average of GDP, RDF and GFS, all on a real per-capita basis during the sample period.

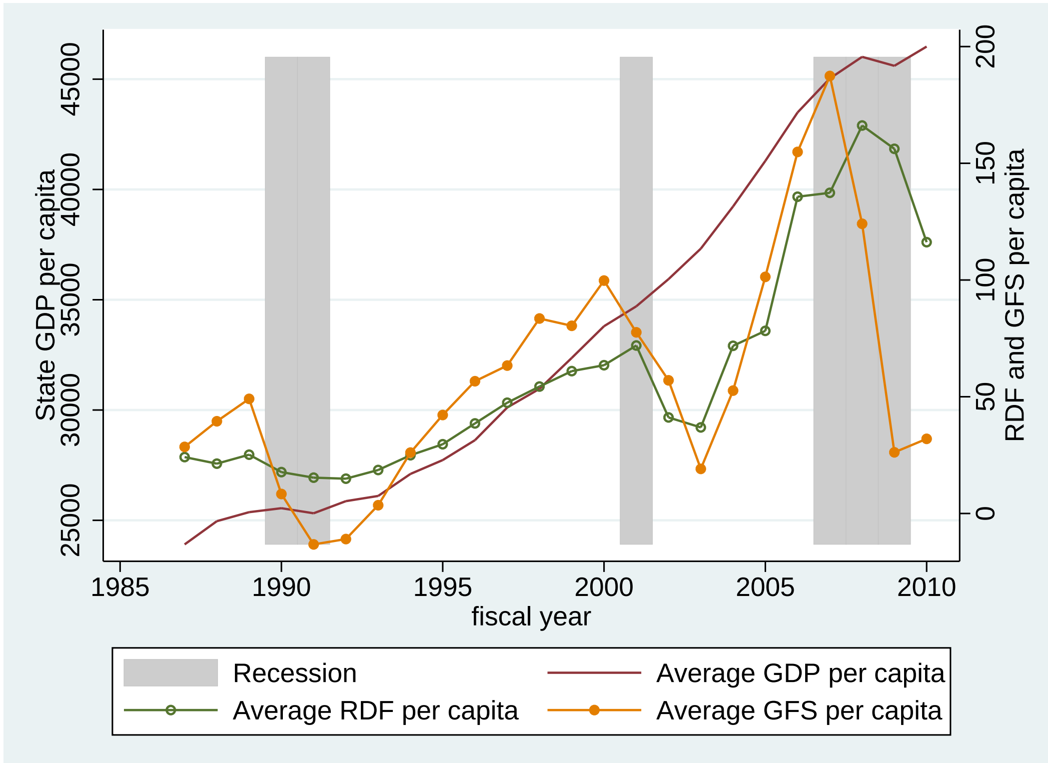

Figure 3.1: Average Aggregate Real per Capita GDP, RDF and GFS during 1987-2010

Note: Three time-series variables (state GDP, RDF and GFS) in the above figures are expressed in annual average real per-capita terms across all states in the sample period of 1987-2010. GDP is measured at the end of the calendar year. RDF and GFS are balances in the funds at the end of the fiscal year.

The empirical specification is as follows:

$$Y_{i,t+1} - Y_{i,t} = \beta + \beta_F * (F_{i,t} - F_{i,t-1}) + \beta_X * (X_{i,t} - X_{i,t-1}) + state_i + year_t + e_{i,t} \quad (3.1)$$

where Y is real GDP per capita and F is real RDF balance per capita at the end of the year 't', X is other variables for controlling their effects (lags of dependent variable as discussed below) and e is idiosyncratic error term representing macroeconomic shocks.

Table 3.1: Data and Sources

Variables	Sample Period	Source
Nominal Gross Domestic Product (GDP)	1987-2010	Bureau of Economic Analysis (BEA)
Rainy day fund balance (RDF)	1987-2010	Hou (2013)
General Fund Surplus (GFS)	1987-2010	Hou (2013)
Existence of Rainy day fund	1987-2008	Hou (2013); Rose and Smith (2011)
Real Gross Domestic Product (1997 US \$)	1987-1997	Bureau of Economic Analysis (BEA)
Real Gross Domestic Product (2009 US \$)	1998-2010	Bureau of Economic Analysis (BEA)
Population	1987-2010	U.S. Census Bureau
Unemployment Rate	1987-2010	U.S. Census Bureau

Table 3.2: Summary Statistics in Level

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
State GDP	33,453.9	9,706.7	15,468.5	77,393.9
Rainy Day Fund Balance	61.2	175.9	0	2,839.2
General Fund Surplus Balance	57.9	204.5	-714.7	1,322.1
Population	5,978,739.2	6,369,394.3	453,690	37,336,011
Unemployment Rate	5.4	1.8	2.2	13.7

Note: State GDP, Rainy Day Fund and General Surplus Fund are in real per-capita 1997 US\$. Population is in persons. Unemployment rate is in %.

Observations are at state 'i' and year 't'. *state* and *year* are state-specific and year-specific fixed effects respectively. The key parameter of interest is the coefficient $\hat{\beta_F}$ that measures the one-period-ahead effect on real GDP per capita for a one-dollar increase in real RDF balance per capita.

One may suspect that the RDF balance may be endogenous to idiosyncratic shocks emanating from the economy, monetary policy, or fiscal policy. However, we note that the savings in RDFs are predetermined and that the change in RDF balance plausibly may not correlate with the contemporary shocks in the next period. However, the changes in RDFs may correlate with past shocks since states determine the savings in RDFs after an economy's condition is realized. The spending from RDFs may

Table 3.3: Summary Statistics in Changes

Variable	Mean	Std. Dev.	Min.	Max.	N
Changes in State GDP	981.3	1,203.5	-11,198.4	11,313.7	989
Changes in Rainy Day Fund	4.0	85.8	-974.2	1,369.0	989
Changes in General Surplus Fund	0.2	99.3	-921.6	920.4	989

Note: All variables in the table are in 1997 US $. State GDP is one period ahead change in real per capita output. Rainy Day Fund and General Surplus Fund are one period changes in real balance per capita from the last period.

also spill over to other states.[2] These funds are specifically designed to receive excess revenues during good times while withdrawals are restricted for use in bad times. In some states, for example Virginia, deposits are made based on the average revenue growth rate over the preceding six years; 50% of the realized surplus revenue above the trend is automatically deposited in the RDF. If the growth rate of adjusted personal income in Ohio exceeds 1.4 percent, the excess percentage is multiplied by the general fund to transfer to the RDF. Several states require legislature approval for such transfers; such approval takes time. For example, a super majority of votes in the Iowa legislature is required for withdrawal from the RDF. Rose and Smith (2011) and Douglas and Gaddie (2002) offer more details on these practices.

We use changes in GFS next period to control the GFS's effects on output changes in the next period. The GFS measures revenue surplus over expenditure in a fiscal year. Hence, the change in GFS is endogenous to the economy's condition. This endogeneity clearly shows that OLS estimation of the equation (3.1) is problematic because of serial correlation and potential endogeneity, causing the estimates to be biased and inconsistent. Because of legitimate concerns over endogeneity, we employ the dynamic panel estimator proposed by Arellano and Bond (1991). This estimator uses the generalized method of moments (GMM) estimator, which takes the equation's first difference (3.1) to eliminate the state-specific unobserved effects. Generating instruments from dependent and independent variables in the model, the estimator

[2] Our specifications do not control for spending spillovers across states. Following Nakamura and Steinsson (2014), we refer to these multipliers as open-economy output multipliers.

is also most appropriate as it is designed for longer panels and short time periods. To implement the estimator, we modify equation (3.1) as follows:

$$Y_{i,t+1} - Y_{i,t} = \beta_F * (F_{i,t} - F_{i,t-1}) + \beta_X * (X_{i,t} - X_{i,t-1}) + year_t + e_{i,t} \tag{3.2}$$

where Y is real GDP per capita and F is real RDF balance per capita at the end of the year 't', X is the dependent variable's lag and e is an idiosyncratic error term representing macroeconomic shocks. Observations are at state 'i' and year 't'. *year* are year-specific fixed effects that states face (for example, shocks during recessions years). This specification assumes that states facing exogenous fiscal shocks respond through deposits or withdrawals from the RDF and that the changes are uncorrelated to the idiosyncratic error. However, GDP growth in one year might affect GDP growth in the subsequent year. To control the lagged effect in the next period, we include one lag of our dependent variable in the specification. This specification is largely consistent with the literature on output multipliers, which rarely use covariates other than the variables of interest in order to avoid endogeneity and multi-collinearity. Nearly all studies employ an instrument variable for identification purposes. In this sense, our specification is unique because we use the dependent and independent variables' lags to generate instruments while employing the Arellano-bond estimator as the dynamic panel-data estimator.

3.4.1 Average Output Multiplier of Rainy Day Fund

Table 3.4 and 3.5 summarize our main empirical results. In Table 3.4, we present four alternative estimates, including models accounting for the potential of endogeneity, but these models do not satisfy the Sargan specification test. Table 3.5 presents two additional models that satisfy the Sargan specification test. In Table 3.4, column (1) treats RDF changes as exogenous while column (2) treats the changes in RDF as predetermined. Column (3) treats the changes in RDF predetermined while GFS changes are endogenous. The last column (4) treats both RDF and GFS changes as endogenous. The treatment of the variables as exogenous, predetermined, or endogenous lets the variable's correct set of lags be employed as instruments in the estimation. In Table 3.5, column (1) uses the two dummy variables, Unified Republic Government and Unified Democratic Government, as exogenous covariates and also instruments. These dummy variables take the value of 1 if the governor is affiliated with the respective political party and if the political party governs the majority of the state legislature. For a divided government, the dummy variables take the value of 0. Additionally, column (2) controls the state-specific income differences. It is encouraging that, in general, the results are very similar across the models. The RDF variable's coefficient is significant across the models, suggesting that the average output multipliers are in the range of 1.5-1.6. These estimates suggest that depositing one dollar into the RDF would decrease the next period's output by just over $1.50. The RDF variable's sign is negative as we expect since states on average deposit money in their RDF (Table 3.3). The coefficient in the changes in GFS is not statistically significant, but the sign is negative. States on average deposit into the GFS (Table 3.3), but the changes in GFS are merely transfers of funds to be applied in the fiscal year. For example, several states use GFS as a source of RDF. Our results suggest the changes in GFS have on average no statistically significant impact on the economy. These results may indicate that on average what is generated as a surplus is returned via tax cuts or is used to support spending.

To put the multipliers into perspective, we expect that the output multiplier for RDF changes would be similar in size to government spending multipliers that have been reported in the literature. For example, Auerbach and Gorodnichenko (2012) report spending multipliers from 1 to 2.12 consisting of the consumption spending multiplier (1.21) and the defense and nondefense spending multipliers (1.16 and 1.17, respectively). Likewise, Nakamura and Steinsson (2014) report state government spending multipliers from 1.4 to 1.6. Our multipliers are in a similar range to these multiplier estimates.

Table 3.4: Output Multipliers of Rainy Day Fund

	(1)	(2)	(3)	(4)
Changes in RDF	-1.550***	-1.503**	-1.602***	-1.578***
	(0.465)	(0.589)	(0.549)	(0.548)
Changes in GFS	-1.412	-1.430	-1.093	-1.113
	(1.509)	(1.681)	(1.625)	(1.661)
N	804	804	804	804

Note: The table reports output multipliers for a $1 increase in RDF. In all models, the dependent variable is the one period ahead of change in real per-capita state GDP and employs the Arellano-Bond estimator. Column (1) reports the estimators when changes in RDF are treated as exogenous. Column (2) reports the estimation when RDF changes are treated as predetermined. Column (3) reports the estimators when GFS changes are treated as endogenous, and RDF changes are treated as predetermined. Finally, Column (4) reports the estimators when both RDF and GFS changes are treated as endogenous. To save space, the coefficients for the time-fixed effects and lagged variables are suppressed. Robust standard errors are in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3.4.2 Multipliers During High and Low Unemployment Periods

To determine how big multipliers are during recessions, we investigate the multipliers during high and low unemployment periods. During periods characterized by significant labor market slackness in the economy, states are likely to be under pressure to increase spending that may require drawing funds from RDF. The existing literature generally notes that the multipliers during a recession should be higher than during expansionary periods. Our interest is in finding these multipliers' relative sizes for the changes in RDFs. Nakamura and Steinsson (2014) use the measure of state-level unemployment rates as the variable to indicate if the states are undergoing periods of weak economic growth. We define the high and low economic slack periods as the periods during which the state-level unemployment rate is higher or lower than the unemployment rate's median level in each state across all periods. We follow Nakamura's (2014) empirical specification that includes all observations across states for high and low unemployment rates in the sample period, but the method does not

Table 3.5: Output Multipliers of Rainy Day Fund: Additional Exogenous Instruments

	(1)	(2)
Changes in RDF	-1.573***	-1.466***
	(0.419)	(0.398)
Changes in GFS	0.0639	0.265
	(0.596)	(0.349)
Personal income		-0.863***
		(0.200)
Year	121.6***	780.2***
	(42.47)	(152.2)
Unified Republic Govt	-156.4	-123.8
	(211.8)	(202.3)
Unified Democratic Govt	3.886	-41.98
	(112.9)	(149.4)
N	579	660

Note: The table reports the two models' output multipliers that include additional variables to be used as instruments. In both models, the dependent variable is the one period ahead of change in real per-capita state GDP and employs the Arellano-Bond estimator. Column (1) has four lags of dependent variable as covariates, and column (2) has two lags of dependent variable as covariates. The coefficients for the time-fixed effects and lagged variables are suppressed to save space. Robust standard errors are in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

identify the states that might be depositing during high-unemployment periods or withdrawing during low-unemployment periods. As a result, the coefficients are not estimated precisely. We also examine the two specifications that include observations when states withdraw or deposit. We do not find statistically significant results in either case, suggesting no clear pattern of how states' RDF withdrawals or deposits in general affect the outputs.

As an alternative approach, we examine only the states that on average either net withdraw or deposit funds during the sample period. We run the regression Eq. (3.2) to get the coefficients in the periods of high and low unemployment. Table 3.6 and

3.7 summarize the RDF and GFS data for the high and low unemployment periods. During recessions, on average the states that net withdraw from RDF simultaneously also deposit in the GFS. In expansionary periods, the deposit in RDFs is much bigger than the deposit in the GFS.

Table 3.6: High Unemployment Period: Summary Statistics

Variable	Mean	Std. Dev.	Min.	Max.	N
Changes in State GDP	927.8	959.9	-2,553.9	4,062.2	204
Changes in RDF	-8.2	52.7	-561.9	113.4	204
Changes in GFS	4.2	101.7	-482.4	644.1	204

Table 3.7: Low Unemployment Period: Summary Statistics

Variable	Mean	Std. Dev.	Min.	Max.	N
Changes in State GDP	1,096.1	1,570.2	-11,198.4	11,313.7	314
Changes in RDF	17.1	140.9	-974.2	1,369.0	314
Changes in GFS	1.3	124.3	-921.6	920.4	314

Table 3.8 summarizes the results. Column (1) reports the coefficients during periods with high unemployment for states that on net withdraw during the sample period. Column (2) reports the coefficients for periods of low unemployment for states that deposit on net during the sample period. The RDFs' multipliers in the period of high unemployment are higher than the period of low unemployment. This finding is consistent with the literature. The results suggest that the multiplier in recessions (high unemployment) is 3.4 while the multiplier in expansions is 0.6. However, the estimate for expansions is not statistically significant. This finding suggests that in recessionary periods the states that on net withdraw \$1 on average have output increased by \$3.4 while in expansionary periods the impact is effectively nil. Also, changes in GFS during the recessionary period is not significant, but those changes are significant in the expansionary period. This result could reflect accrual of tax revenue

that is then used to retire debt or is placed in a fund, such as a transportation fund, for future use.

Table 3.8: Multipliers of Rainy Day Fund: High vs Low Unemployment Period

	(1) High Slackness in Unemployment	(2) Low Slackness in Unemployment
Changes in RDF	-3.376**	-0.644
	(1.711)	(0.513)
Changes in GFS	0.985	-2.864*
	(0.686)	(1.735)
N	167	304

Note: The table reports output multipliers for a $1 increase in RDF during periods of high and low unemployment. Both models use the Arellano-Bond estimators. In all models, the dependent variable is the one period ahead of change in states' real per-capita GDP. Column (1) reports the estimators for the high unemployment-rate period for states that on average have net withdrawal from RDF in the sample period. Column (2) reports the estimators for the expansionary period of states that on average have net deposits in the sample period. To save space, the coefficients for the time-fixed effects and lagged variables are not shown in the table. Robust standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3.4.3 Impact of RDFs During Election Years

Rose (2008) is the first to show that states withdraw significant amounts from the RDF during election years. She shows that nearly three times more funds are withdrawn from states during a deficit shock in an election year compared to non-election years. In this section, we investigate the impact of such withdrawals from RDF in election years compared to non-election years. To do so, we modify our specification to include an interaction term by multiplying a dummy indicator variable by our RDF variable. The dummy indicator represents 1 for gubernatorial election years and 0 for non-gubernatorial election years. Table 3.9 summarizes the results. Consistent with Rose (2008), the estimated coefficient for changes in the RDF during election years are nearly twice as big as RDFs' average impact in the sample period. Also, the impact of withdrawal during an election year is nearly similar in size to the impact during recessionary periods. This finding suggests that there is substantial impact on state outputs for withdrawals from RDF during election years compared to non-election years.

Table 3.9: Multipliers of Rainy Day Fund: Election Years

	(1)
Changes in RDF	-0.811*
	(0.418)
Changes in GFS	-1.484
	(1.832)
Changes in RDF in election years	-3.336**
	(1.473)
Changes in GFS in election years	0.854
	(2.366)
N	804

Note: The table reports output multipliers for a $1 increase in RDF in election years. The regression employs the Arellano-Bond estimator. The dependent variable is the one period ahead of change in states' real per-capita GDP. To save space, the coefficients for the time-fixed effects and lagged variables are not shown in the table. Robust standard errors are in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3.5 Conclusion

Rainy day funds are potentially important mechanisms subnational governments use to smooth expenditures during periods of fiscal stress. RDFs may have differential impacts during different states of the economy. Fund accumulation removes purchasing power from the economy during periods of economic expansion; such removal may dampen growth. On the other hand, the disbursement of RDFs may inject stimulus into the economy when funds are used during periods of fiscal and economic stress. While these countercyclical influences on economic performance are not the motivation for using RDFs, any effects may be important to the states' economic health and to overall fiscal and monetary policy coordination across branches of the fiscal hierarchy. Our results show that the fund has an impact on output, which is slightly lower than estimates coming from directly observable changes in government expenditure. Our evidence also points to a wider differential impact of RDFs during periods of relatively high and low unemployment periods. Our results show that the RDF has a bigger impact during recessionary periods. Also, RDF's impact during election years is as big as in recessionary periods.

Using unique data on RDFs and GFS for 43 U.S. states in 1987-2010, we find that on average a deposit of one dollar in RDF would reduce output in the next period by about \$1.50. Such an impact on outputs is greater during recessionary periods characterized by high unemployment. The RDF's output multiplier is about 3.4 in recessionary periods and is nil in expansionary periods. During election years, the impact is as high as 3.4, similar to the impact in recessionary periods.

These findings have several important policy implications. First, while subnational governments do not use RDFs to affect economic growth, our results suggest that they may do so. Second, our results suggest the need for coordinating monetary and fiscal policies across federal and state governments, especially as state RDF balances grow, thus providing evidence that the states' budget stabilization funds have implications for economic growth.

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Appendix

Appendix A

Environmental Policy Instruments Under Terms of Trade and Business Cycle Uncertainties

A.1 AR(1) Process

Table A.1: AR(1) Process of Productivity and Terms of Trade Shocks

	(1) Total Factor Productivity	(2) Terms of Trade
ARMA		
L.ar	0.533***	0.319**
	(0.0967)	(0.136)
sigma		
Constant	0.0149***	0.0296***
	(0.00177)	(0.00294)
chi2	30.42	5.472
N	61	61

Note: This table shows the estimates of serial autocorrelation (persistency) for real GDP (in terms of trillion dollars Canadian GDP) and the relative price of import to exports, respectively. We use AR(1) process to estimate the coefficients using hp-filtered smoothing parameter of 100 for both series. The standard deviation of the shocks for each variable is shown as 'sigma'. Standard errors are in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

A.2 Persistent Shocks

Table A.2: Variations Under the 1 s.d. Positive Productivity Shock

Variables	No policy	Cap	Tax	Intensity Target
Consumption	1.74	1.49	1.74	1.72
Labor	1.44	1.25	1.45	1.43
Investment	19.00	16.69	19.42	18.79
Output	3.62	3.13	3.64	3.60
Emission	3.61	0.00	3.64	3.60

Note: The table shows the coefficient of variations of key variables under the productivity shock of 1.5 times the standard deviation with 90% persistency. The coefficient of variation is the standard deviation divided by the theoretical mean level (in percentage points).

Table A.3: Variations Under the 1 s.d. Negative Terms of Trade Shock

Variables	No policy	Cap	Tax	Intensity Target
Consumption	3.88	3.86	3.88	3.88
Labor	0.44	0.43	0.44	0.43
Investment	1.71	1.54	1.73	1.69
Output	0.26	0.22	0.26	0.26
Emission	0.26	0.00	0.26	0.26

Note: The table shows the coefficient of variations of key variables under the terms of trade shock of 1.5 times the standard deviation with 90% persistency. The coefficient of variation is the standard deviation divided by the theoretical mean level (in percentage points).

Table A.4: Welfare Differences Across Environmental Policy Instruments Under Persistent Shocks

Description	Change from No Policy				% Change from No Policy		
	No policy	Cap-and-Trade	Tax	Intensity Target	Cap-and-Trade	Tax	Intensity Target
	Productivity Shock						
Change in welfare		-0.6089	-0.5740	-0.1972	-3.36%	-3.17%	-1.09%
	Terms of Trade Shock						
Change in welfare		-0.5766	-0.5796	-0.1973	-3.11%	-3.13%	-1.07%

Note: The table shows the changes in welfare across environmental policy instruments from the no policy case under the shocks of 1.5 times their corresponding standard deviations with 90% persistency. In estimating the changes, total welfare is calculated as the sum of discounted welfare keeping labor fixed from the steady state in the no policy case.

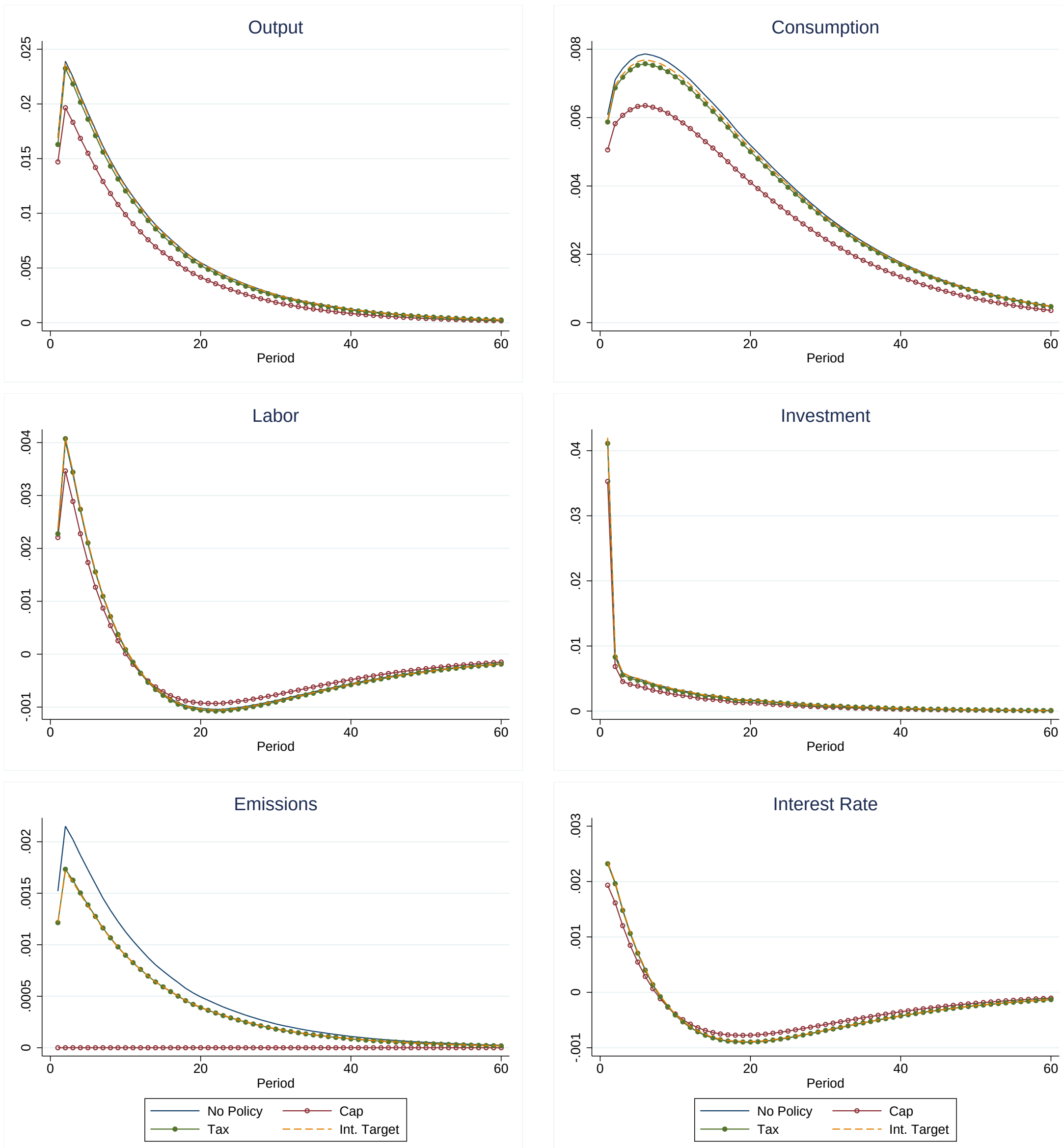

Figure A.1: Impulse Responses Under the Productivity Shock (Panel A)

Note: The figures show the impulse responses of output, consumption, labor, capital, emissions, and interest rate in response to the positive productivity shock of 1.5 times the standard deviation with high (90%) persistency. The shock is shown on the bottom right corner panel in Figure A.2. Zero on the vertical axis on each graph represents corresponding variable's steady state level. The responses are in terms of deviation from the steady state level.

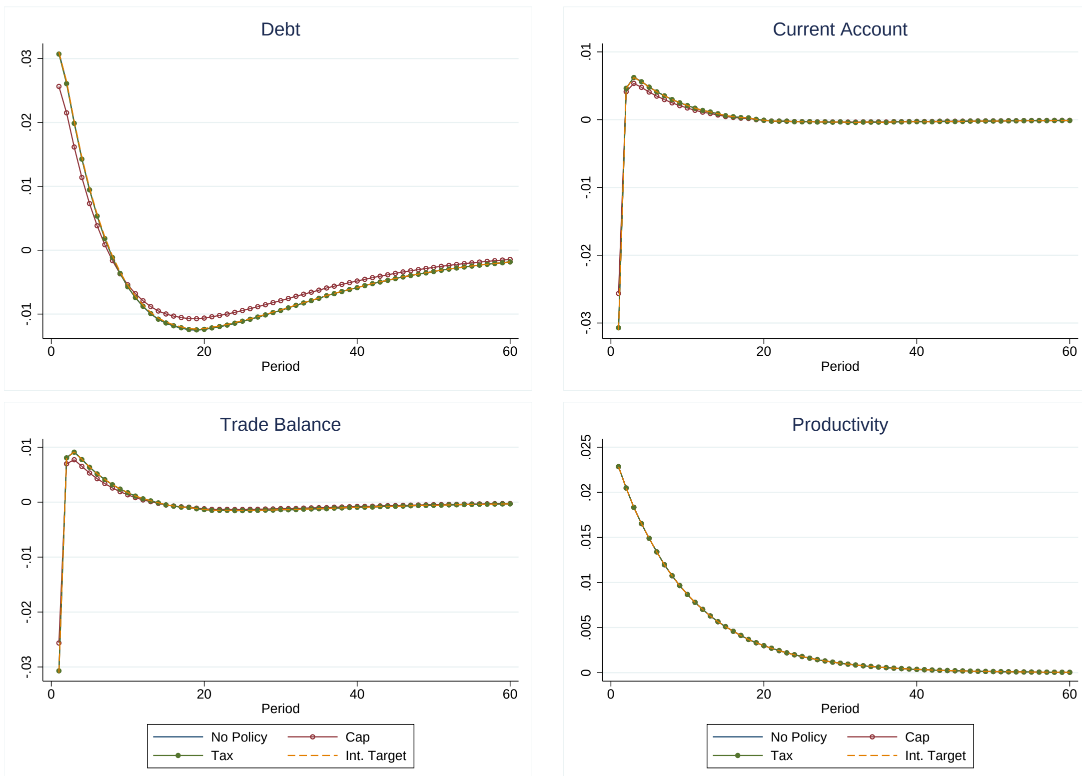

Figure A.2: Impulse Responses Under the Productivity Shock (Panel B)

Note: The figures show the impulse responses of debt, current account and trade balance in response to the positive productivity shock of 1.5 times the standard deviation with high (90%) persistency. The shock is shown on the bottom right corner panel. Zero on the vertical axis on each graph represents corresponding variable's steady state level. The responses are in terms of deviation from the steady state level.

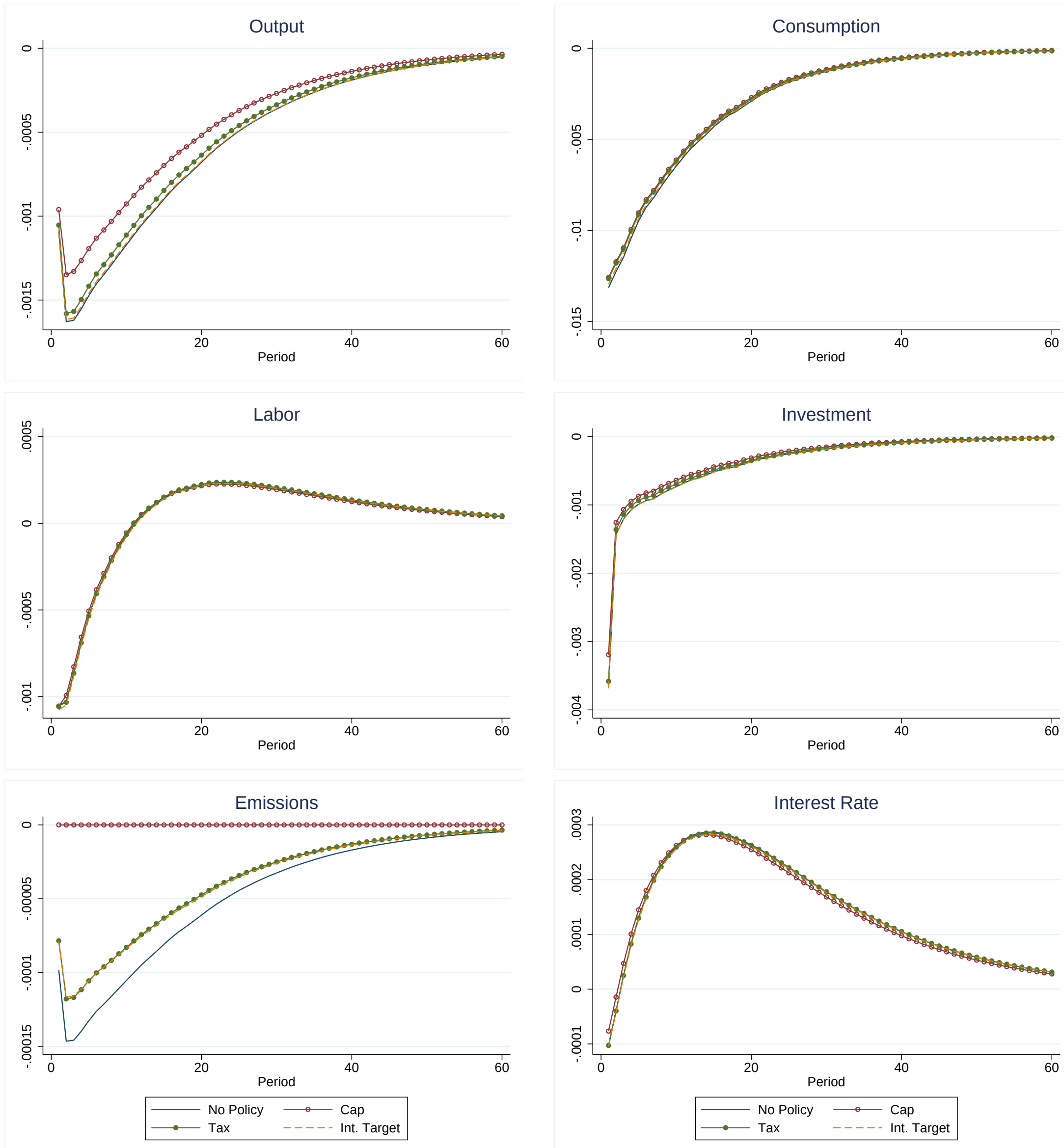

Figure A.3: Impulse Responses Under the Terms of Trade Shock (Panel A)

Note: The figures show the impulse responses of output, consumption, labor, capital, emissions and interest rate in response to the negative terms of trade shock of 1.5 times the standard deviation with high(90%) persistency. The shock is employed through a positive shock to the relative price of consumption as shown on the bottom right corner in Figure A.4. Zero on the vertical axis on each graph represents corresponding variable's steady state level. The responses are in terms of deviation from the steady state level.

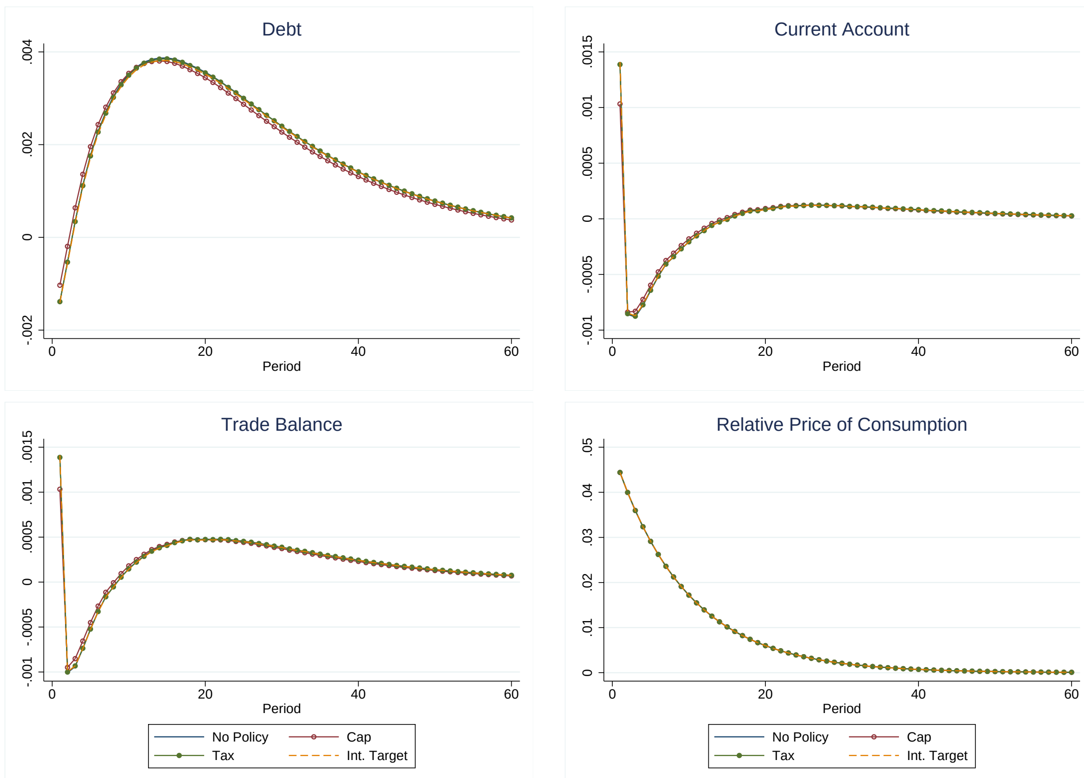

Figure A.4: Impulse Responses Under the Terms of Trade Shock (Panel B)

Note: The figures show the impulse responses of debt, current account and trade balance in response to the negative terms of trade shock of 1 standard deviation with high(90%) persistency. The shock is employed through a positive shock to the relative price of consumption as shown on the bottom right corner. Zero on the vertical axis on each graph represents corresponding variable's steady state level. The responses are in terms of percentage deviation from the steady state level.

A.3 Highly Correlated Shocks

Table A.5: Variations Under Highly Correlated Shocks

Variables	No policy	Cap	Tax	Intensity Target
	$\nu = -0.045$			
Consumption	2.30	2.26	2.30	2.30
Labor	1.26	1.13	1.27	1.25
Investment	10.52	9.06	10.71	10.35
Output	2.21	1.93	2.22	2.20
Emission	2.21	0.00	2.22	2.20
	$\nu = -0.45$			
Consumption	2.47	2.42	2.48	2.47
Labor	1.43	1.29	1.43	1.41
Investment	11.07	9.55	11.26	10.89
Output	2.31	2.01	2.31	2.30
Emission	2.31	0.00	2.31	2.30
	$\nu = 0.045$			
Consumption	2.26	2.23	2.26	2.26
Labor	1.23	1.09	1.23	1.21
Investment	10.40	8.95	10.59	10.23
Output	2.19	1.91	2.20	2.18
Emission	2.19	0.00	2.20	2.18
	$\nu = 0.45$			
Consumption	2.09	2.08	2.09	2.09
Labor	1.04	0.91	1.04	1.03
Investment	9.82	8.44	10.01	9.67
Output	2.09	1.82	2.10	2.09
Emission	2.09	0.00	2.10	2.09

Note: The table shows the coefficient of variations for 1 standard deviation terms of trade and total factory productivity shocks under the selected correlations between the shocks. The coefficient of variation is the standard deviation divided by the theoretical mean level (in percentage points).

Appendix B

Emissions Leakage, Environmental Policy and Trade Frictions

The reduced form solutions of $\hat{h_x}$, $\hat{y}$, $\hat{x}$, and $\hat{e}$ in section 2.3 are change in the manufacturing sector's labor supply

$$\hat{h_x} = -\frac{\theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}\hat{T}; \tag{B.1}$$

change in the service sector's outputs

$$\hat{y} = \alpha_2\frac{\theta_{hx}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}\hat{T}; \tag{B.2}$$

change in the manufacturing goods sector's outputs

$$\hat{x} = -\alpha_1\frac{\theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}\hat{T}; \tag{B.3}$$

and change in emissions

$$\hat{e} = -\left(\frac{\alpha_1\theta_{hy}}{\theta_{hx}(1-\alpha_2)+\theta_{hy}(1-\alpha_1)}\frac{\xi}{1-\xi}+\frac{1}{1-\xi}\right)\hat{T}. \tag{B.4}$$

Proof of Proposition 1:

Income effect on consumption

From Eq. (2.22)

$$\text{Income effect} = \frac{\alpha_2 S_y \theta_{hx} - \alpha_1 S_x \theta_{hy}}{\theta_{hx}(1-\alpha_2) + \theta_{hy}(1-\alpha_1)} \tag{B.5}$$

Plugging $\alpha_1 = \frac{1}{(1-\xi)} \frac{w h_x}{e^{\xi} x^{1-\xi}}$ and $\alpha_2 = \frac{w h_y}{p\, \mu\, y}$ from the firm's first order conditions (where w is wage in an initial equilibrium) and plugging the shares $S_x = \frac{e^{\xi} x^{1-\xi}}{C}$, $S_y = \frac{p\, \mu\, y}{C}$, $\theta_{hx} = \frac{h_x}{\bar{h}}$ and $\theta_{hy} = \frac{h_y}{\bar{h}}$, it yields:

$$\text{Income effect} = \frac{1}{C} \frac{w h_x h_y}{h_x(1-\alpha_2) + h_y(1-\alpha_1)} \left(-\frac{\xi}{1-\xi}\right) \tag{B.6}$$

which is negative.

Terms of trade effect on consumption

From Eq. (2.22)

$$\text{Terms of trade effect} = -S_x \tag{B.7}$$

which is negative.

Since, $\hat{c_x} = \hat{c_y}$ (Eq. (2.19)), increased emissions tax has negative effect both goods and services' consumption in a small open economy.

Appendix C

Output Multipliers and State Rainy Day Funds

C.1 Rainy Day Fund Rules

Table C.1: RDF Rules for Deposit and Withdraw in 2002

State	**Deposit Rule**	**Withdraw Rule**
Alabama	20 percent from preceding fiscal year up to $75 million; appropriated by Legislature	2/3 vote of the legislature
Alaska	Unexpended balance and by appropriations; oil and gas litigation/disputes settlements	Appropriation; 3/4 vote of Legislature
Arizona	No limit	By formula with majority legislative appropriation; non-formula with 2/3 Legislature approval
Arkansas	-	-
California	Appropriation by Legislature	Appropriation by Legislature
Colorado	Constitutional 4 percent of revenues	Procedure has not been tried thus far
Connecticut	5 percent of net General Fund appropriations	Fund deficit after the books have been closed
Delaware	No greater than 5 percent of gross General Fund revenues	3/5 vote of Legislature for unanticipated deficit or revenue reduction resulting from legislative action
Florida	Appropriations Act	Governor declared emergency or legislative appropriations to cover revenue shortfalls
Georgia	3 percent of prior year net revenue	Revenue shortfall during recent year
Hawaii	No limit. Receives 40 percent of tobacco settlement	2/3 vote of Legislature
Idaho	If General Fund grew more than 4 percent in the previous Fiscal Year 1 percent is transferred to the Budget Stabilization Fund. Capped at 5 percent of the General Fund.	Legislative action
Illinois	$225,000,000 (no limit)	Comptroller can direct transfers to General Fund
Indiana	Capped at 7 percent of state revenue	Statutory formula
Iowa	5 percent of net General Fund Revenue	Simple majority of General Assembly for 40 percent of the fund. 3/5's majority of General Assembly for 60 percent of the fund; Simply majority of General Assembly

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Table C.1 – continued from previous page

State	Deposit Rule	Withdraw Rule
Kansas	-	-
Kentucky	Goal of 5 percent of General Fund Budget	Budget Reduction Plan- statute
Louisiana	Revenues exceeding 750 million from minerals rents	1/3 of fund with legislative approval
Maine	6 percent of General Fund in immediately preceding Fiscal Year	Legislation
Maryland	5 percent of estimated General Fund revenues for that fiscal year	Act of the General Assembly or authorized specifically in Budget Bill
Massachusetts	-	Appropriation
Michigan	Capped at 10 percent of General Fund year end balance	Statutory formula
Minnesota	Set in Statute at $622 million	Approval from the Governor and after consulting Legislative Advisory Commission
Mississippi	7.5 percent of the General Fund by appropriation	Appropriation
Missouri	Minimum 7.5 but can increase up to 10 percent of net general revenue by legislative approval	Legislative disapproval
Montana	-	-
Nebraska	Statute	Statute
Nevada	By comptroller, 10 percent of the General Fund	Statute
New Hampshire	5 percent by statute	Statute
New Jersey	50 percent of amount by which actual revenues exceeds anticipated revenues; Capped at 5 percent of anticipated revenues.	Legislative approval
New Mexico	-	Legislative approval
New York	State finance law	Can be used when a deficit is incurred for temporary loans
North Carolina	1/4 of Credit Balance, capped at 5 percent of the appropriated amount in the preceding year for the General Fund Operating Budget.	Legislative approval
North Dakota	Any amount over $40 million at the end of biennium.	Actual revenues must be 2.5 percent below forecast
Ohio	By statute the stated intent is to have amount approximately 5 percent of the General Revenue fund for the preceding fiscal year	Legislative action necessary

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Table C.1 – continued from previous page

State	Deposit Rule	Withdraw Rule
Oklahoma	Maximum of 10 percent of preceding year's general revenue	Up to half if revenue certification is below previous year, half can be used upon declaration of the Governor and 2/3's vote of Legislature, or by legislative declaration of emergency and 3/4's legislative vote.
Oregon	-	-
Pennsylvania	Goal of 6 percent of General Fund revenue estimates.	2/3 legislative vote with the Governor's request
Rhode Island	3 percent of resources	Used to cover deficit caused by general revenue shortfall
South Carolina	2-3 percent of General Fund Revenue of last Fiscal Year	Use when year-end deficit is projected
South Dakota	5 percent of General Fund in prior year's General Appropriation Act	Legislative appropriation
Tennessee	By appropriation	Revenue Shortfall
Texas	Capped at 10 percent of general revenue fund deposits during the preceding biennium	3/5 vote of each house of Legislature to remedy deficits after budget adoption. Other appropriations from this fund require a 2/3's vote.
Utah	-	-
Vermont	Capped at 10 percent of average annual tax revenues on income and retail sales for the 3 years immediately preceding.	Legislative appropriation
Washington	State general fund revenues in excess of expenditure limit by Treasurer	Legislative appropriation
West Virginia	Capped at 5 percent of the General Fund Appropriation	Legislative appropriation
Wisconsin	50 percent of unanticipated revenues	Legislative appropriation
Wyoming	Appropriation of unexpected appropriated balance	Legislative appropriation

Source: Budget Processes in the States. National Association of State Budget Officers. January 2002

Table C.2: RDF Rules for Deposit and Withdraw in 2008

State	Deposit Rule	Withdraw Rule
Alabama	20 percent from preceding fiscal year up to $75 million; appropriated by Legislature	2/3 vote of the legislature
Alaska	Unexpended balance and by appropriations; oil and gas litigation/disputes settlements	Appropriation; 3/4 vote of Legislature
Arizona	**7 percent of Current year General Fund**; No limit	By formula with majority legislative appropriation; non-formula with 2/3 Legislature approval
Arkansas	Statutory	Appropriation
California	Appropriation by Legislature	Appropriation by Legislature
Colorado	Constitutional 4 percent of revenues	**Constitutional Act**
Connecticut	**10 percent of General Fund appropriations**	Fund deficit after the books have been closed
Delaware	No greater than 5 percent of gross General Fund revenues	3/5 vote of Legislature for unanticipated deficit or revenue reduction resulting from legislative action
Florida	**5 percent of the last completed fiscal year's net revenue collection for the General Revenue Fund; Not exceeding 10 percent of the last completed fiscal year's net revenue**	Governor declared emergency or legislative appropriations to cover revenue shortfalls
Georgia	**10 percent of prior year net revenue**	Revenue shortfall during recent year
Hawaii	No limit. **24.5 percent of tobacco settlement**	2/3 vote of Legislature
Idaho	If General Fund grew more than 4 percent in the previous Fiscal Year 1 percent is transferred to the Budget Stabilization Fund. Capped at 5 percent of the General Fund.	Legislative action
Illinois	-	Comptroller can direct transfers to General Fund
Indiana	Capped at 7 percent of state revenue	Statutory formula
Iowa	**7.5 percent of net General Fund Revenue**	Simple majority of General Assembly for 40 percent of the fund. 3/5's majority of General Assembly for 60 percent of the fund; Simply majority of General Assembly
Kansas	-	-

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Table C.2 – continued from previous page

State	Deposit Rule	Withdraw Rule
Kentucky	Goal of 5 percent of General Fund Budget	Budget Reduction Plan- statute, and Appropriations Act authority
Louisiana	**Revenues exceeding 850 million from minerals rents, 25 percent of nonrecurring revenue which includes General Fund Balance, capped at 4 percent of state revenue, less federal disaster assistance**	1/3 of fund with legislative approval
Maine	**Capped at 12 percent of General Fund revenue in the immediately preceding Fiscal Year, may not be reduced 1 percent of total General Fund revenue in the immediately preceding state fiscal year**	Legislation
Maryland	5 percent of estimated General Fund revenues for that fiscal year	Act of the General Assembly or authorized specifically in Budget Bill
Massachusetts	**Statutory 15 percent of budgeted revenues**	Appropriation
Michigan	Capped at 10 percent of General Fund year end balance	Statutory formula
Minnesota	Set in Statute at $622 million	Approval from the Governor and after consulting Legislative Advisory Commission
Mississippi	7.5 percent of the General Fund by appropriation	Appropriation
Missouri	Minimum 7.5 but can increase up to 10 percent of net general revenue by legislative approval	**Legislative approval by 2/3 vote**
Montana	-	-
Nebraska	Statute	Statute
Nevada	**40 percent of unrestricted fund balance that remains after subtracting 10 percent of ongoing appropriations. Capped at 15 percent of General Fund Operating appropriations**	Statute
New Hampshire	5 percent by statute	Statute
New Jersey	50 percent of amount by which actual revenues exceeds anticipated revenues; Capped at 5 percent of anticipated revenues.	Legislative approval
New Mexico	**The combination of balances is 10 percent of current year recurring appropriations**	Legislative approval

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Table C.2 – continued from previous page

State	Deposit Rule	Withdraw Rule
New York	**2-3 percent of General Fund spending**	Can be used when a deficit is incurred for temporary loans
North Carolina	1/4 of Credit Balance, **capped at 8 percent of the appropriated amount in the preceding year for the General Fund Operating Budget**.	Legislative approval
North Dakota	**$200 million for the 2007-09 biennium and a maximum of 10 percent of general fund after July 1, 2009**.	Actual revenues must be 2.5 percent below forecast
Ohio	By statute the stated intent is to have amount approximately 5 percent of the General Revenue fund for the preceding fiscal year	Legislative action necessary
Oklahoma	Maximum of 10 percent of preceding year's general revenue	Up to half if revenue certification is below previous year, half can be used upon declaration of the Governor and 2/3's vote of Legislature, or by legislative declaration of emergency and 3/4's legislative vote.
Oregon	Cap of 7.5 percent of General Fund revenue in previous biennium	3/5 vote of legislature if certain revenue or economic conditions are met. Can spend up to 2/3 of balance in a biennium.
Pennsylvania	**25 percent of General Fund fiscal year ending surplus. If the fund's ending balance would equal or exceed 6 percent of actual General Fund revenues for the fiscal year in which the surplus occurs, the General Fund transfer would be reduced to 10 percent.**	2/3 legislative vote with the Governor's request
Rhode Island	**5 percent of resources by 2013**	Used to cover deficit caused by general revenue shortfall
South Carolina	2-3 percent of General Fund Revenue of last Fiscal Year	Use when year-end deficit is projected
South Dakota	5 percent of General Fund in prior year's General Appropriation Act	Legislative appropriation
Tennessee	By appropriation	Revenue Shortfall
Texas	Capped at 10 percent of general revenue fund deposits during the preceding biennium	3/5 vote of each house of Legislature to remedy deficits after budget adoption. Other appropriations from this fund require a 2/3's vote.
Utah	No cap	-
Vermont	**Capped at 5 percent of prior year appropriations**.	**Automatic when deficit occurs at year end**

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Table C.2 – continued from previous page

State	Deposit Rule	Withdraw Rule
Washington	State general fund revenues in excess of expenditure limit by Treasurer, **balance capped at 5 percent of general fund revenues**.	Legislative appropriation, **2/3 vote if resulting expenditures do not exceed limit. Otherwise, a vote of the people is required**.
West Virginia	**50 percent of previous fiscal year general revenue surplus is deposited in fund by code.**	Legislative appropriation
Wisconsin	50 percent of unanticipated revenues	Legislative appropriation
Wyoming	**No cap**	Legislative appropriation

Source: Budget Processes in the States. National Association of State Budget Officers. Summer 2008

Vita

Shreekar Pradhan, a Nepalese citizen, had an undergraduate degree in Mechanical Engineering and Master of Science in Renewable Energy Engineering from the Tribhuvan University in Nepal. He worked for over three years in teaching and conducting research at the University's Center for Energy Studies. He also worked in the Energy, Economics and Planning unit at the Asian Institute of Technology (AIT) in Thailand for over two years. In 2011, he completed his Masters in Agricultural Economics in the University of Tennessee's Department of Agricultural and Resource Economics and joined the PhD program in the University's Department of Economics. He earned his PhD in Economics in 2016. He is interested in evaluating environmental and fiscal policies' effects in open economies. Shreekar is also interested in understanding global climate mitigation policies' effects on emerging developing countries' energy systems. He will be joining KAPSARC in Riyadh, Saudi Arabia as a Senior Research Associate in July 2016.